Magnesium Matrix Composites Machining Aspects: A Review

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Abstract:*Due to high demands for energy saving, lightweight materials attract a large amount of research interest. Magnesium is lightweight structural metal. Magnesium and its alloys are used in automotive, aerospace and chemical applications in wide scale that is because of their low density. However, their applications are restricted by their low strength and ductility. By addition of micro and nano-size reinforcements, thus giving them excellent properties to be a hopeful choice for many applications, and improving the mechanical properties. The machining characteristics of magnesium-based (MMCs) have not completely reported so far, for the machining of magnesium-based (MMCs); open literature reported only limited researches. This article focuses on machining of these materials in cases of; Cutting tool failure and wear mechanisms, influence of cutting parameters, cutting forces, Surface finish and Tool materials used.*

Keywords: Magnesium matrix composites, Machining parameters, Wear mechanism,Surface finish.

1. Introduction:

Metal matrix composites (MMCs) are used in a wide range because of their superiority specific properties (properties/weight unit) of stiffness and strength, when compared with monolithic metals, and they show hopeful potential for new products design and production [1,2,3,4,5]. Nevertheless, they are anisotropic, non-homogeneous materials and reinforced with very abrasive elements, this make these materials hard (difficult) to machine [6,7,8]. This will result in significant damage to the workpiece to be machined and higher rates of the tool wear. The machining characteristics of magnesium based composite have not completely reported so far, this paper focuses on machining processes of these materials in cases of; cutting tool failure and wear mechanisms, influence of cutting parameters, cutting forces, surface finish and tool materials used. For magnesium-based (MMCs) machining processes, open literature reported only limited researches. Although, nearly all of the challenges of machining magnesium based composites are similar to which for aluminium-based composites.

1.1 Magnesium:

Magnesium is highly desired lightweight structural metal. Magnesium alloys are (33%), (61%) and (77%) lighter than aluminum, titanium and stainless steels respectively [4,9]. This makes them hopeful prospect as replacement material for these metals. Among the earth crust elements, magnesium is the sixth most abundant element, about (2.1%) of earth crust weight [9,10]. Magnesium and its alloys are used widely in many sectors of applications in aerospace, automobile, chemical and communication industries due to their low density (1.738 g/cm^3) [11,12,13]. However, their low mechanical strength, low modulus, ductility and poor wear resistance limit their applications. Therefore, to reach the required properties, composites of several kinds of reinforcements needed [14].

1.2 Magnesium Matrix Composites:

Metal matrix composites (MMCs) producing by a combination of a light metal called matrix with other elements called reinforcements could be particles or fibers (metal, non-metal, ceramic or organic elements) [14]. When using of one matrix reinforced with two or more elements called hybrid composites. Generally, the major advantages of metal matrix composites over the monolithic metals are [6,7,10,14]:

- High specific strength,
- High limit of elasticity, stiffness, fatigue strength,

- Superior wear and corrosion resistance,
- Improved of damping,
- High strength-weight ratio,
- Thermal expansion decreased,

Table-1: Magnesium mechanical properties compared with some other metals [15].

Mechanical properties	α/β Ti alloy	AISI 4000 series steel	Aluminium alloy	Magnesium alloy	Gray cast iron
Hardness, Brinell	290–411	121–578	28–79	30–600	131–550
Hardness, Vickers	304–480	36–700	29–89	59–100	161–321
Tensile strength, ultimate (MPa)	825–1,580	450–1,970	90–295	90–1,070	118–448
Tensile strength, yield (MPa)	759–1,410	275–1,860	31–285	21–460	65.5–172
Elongation at break (%)	3–18	8–34	1–40	1–75	–
Modulus of elasticity (GPa)	105–125	196–213	68.9–70.0	38–120	62.1–162
Compressive yield strength (MPa)	860–1,280	1650–1,800	0.552–4.60	21–448	572–1,380
Poissons ratio	0.310–0.342	0.270–0.300	0.330–0.350	0.270–0.350	0.240–0.330
Fatigue strength (MPa)	140–1,160	138–772	48.3–110	30–235	68.9–207
Shear modulus (GPa)	41.0–48.3	75–82	0.0483–26.0	16.3–48.0	27.0–65.5

Magnesium matrix composites (Mg-MCs) offer many advantages than monolithic magnesium or its alloys, such as high strength, high elastic modulus, super creep properties, and superb wear resistance at high levels of temperatures [6,9,10]. In contrast, their ductility reduced, this limits their applications. The wished properties achieved by a prudent selection of size and type of the reinforcement particles used. The most used reinforced materials are Silicon Carbide (SiC), Aluminium Oxide (Al_2O_3), Titanium Carbide (TiC), Boron Carbide (B_4C), Carbon Nano-tubes (CNTs) and recently Graghene Nano-Platelets (GNPs) [8,9,10,11,12,14,16]. FU-SHENG Pan et al. [10] for the first time successfully produced magnesium-graphene nanoplatelets composites (Mg/0.3wt%GNPs) in (2015) via semi powder metallurgy process. By adding 0.3wt%GNPs to magnesium matrix resulted an improved in elastic modulus, tensile strength, ultimate tensile strength and Vickers hardness up to (10.0%), (5%), (8%) and (19.3%) respectively.

Table-2: Mechanical properties pure (Mg) compared to (Mg/0.3wt%GNPs) composites [10].

Materials	Elastic Modulus (GPa)	0.2%YS (MPa)	UTS (MPa)	Strain Failure (%)	Vickers Hardness (HV)
Pure Mg	13.2 ± 0.3	187 ± 4	219 ± 5	3.45 ± 0.5	57.5 ± 2
Mg/0.3wt %GNPs	14.6 ± 0.2	197 ± 3.1	238 ± 6	3.11 ± 0.4	68.5 ± 2

2 Machining of Metal Matrix Composites:

Metal matrix composites (MMCs) are non-homogeneous, anisotropic and reinforced with very abrasive elements, this make them hard to machine materials [8,16,17]. Conventional machining operations, such as turning, drilling and milling, are widely used for the cutting of metal matrix composites. For the reason that the reinforcements are brittle and abrasive, the chip separation is achieved by brittle fracture instead of plastic deformation during cutting process. Metal matrix composites machining processes are quite different in many sides from machining processes of monolithic metals and their alloys [8,18].

The major dilemma in the machining of metal matrix composites (MMCs) is the high levels of tool wear and under nominated conditions; this ultimately leads to non-economical or unattainable operational. The very tough and abrasive reinforcement's elements cause extensive tool wear. This can be explained by observing to the tribological system (Fig.1) [6,8].

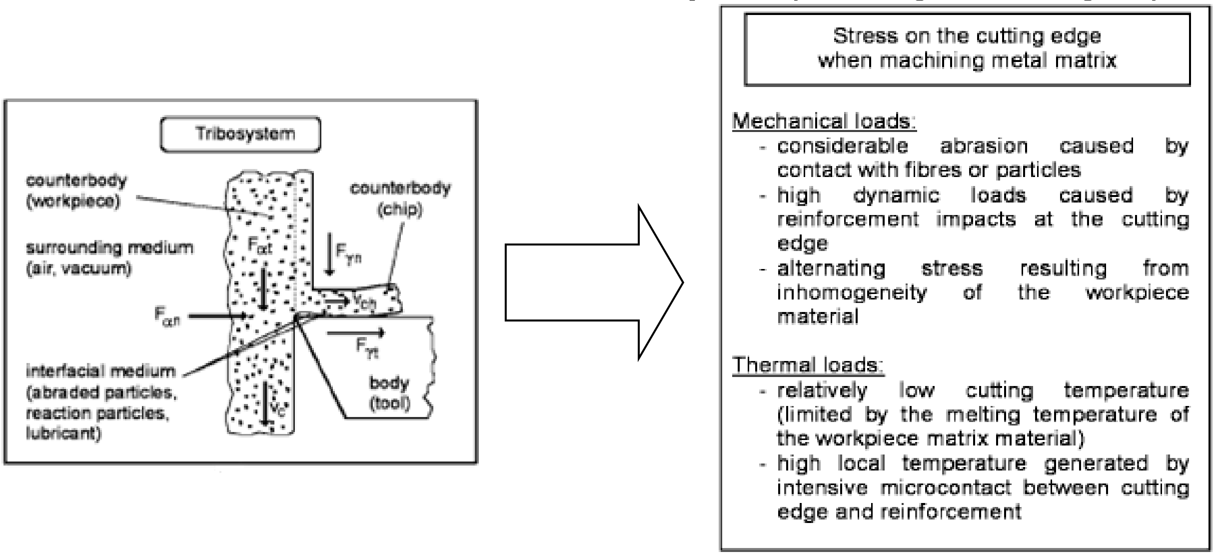


Fig-1: Tribological system in the machining of MMCs [6,8].

The essential reason causing tool wear is the straight contact among the particles of reinforcement elements and the tool cutting edges; this leads to mechanical and thermic loads affecting on the tool cutting edges [6,7,14,16]. The abrasion mechanism is the predominant tool wear, and it generated by both direct impacts of the reinforcement particles at the tool cutting edge and by the sliding movement of the reinforcement particles relative to rake face of the tool. Various wear mechanisms are in charge of the abrasive tool wear. These mechanisms are (micro/cutting), (micro/ploughing), (micro/cracking) and (micro/fatigue) [8].

Aside from tool wear, the processed subsurface integrity of (MMC) is also significant factor. The damage of the reinforcement particles in the friction zone during the machining process, leads to poor in the properties of the finished surfaces of the (MMC) [16,17,19].

3 Chip Formations:

The material in front of the cutting edge undergoes tough plastic deformation and sequent shearing outcomes in chip formation. Chip formation modes of (MMCs) similar to the manner of monolithic metals [16,17]. Thus, the changes in mechanical properties with reinforcement form and allocation in the matrix defines the mechanism of chip formation (shearing, plowing, and cracking) and then effect the machinability of (MMCs) [16]. The chip formation tests will give a clear view of the machining parameters that affect tool wear and surface roughness.

Experimental works accomplished by W. PEDERSEN et. al. [18], using (PVD) (TiCN/TiN) coated (C2) carbide inserts (TPG-322) cutting tool for machining (ZK60A-T5) magnesium matrix with (20vol% SiC) particles of 3-4 μm diameter, it is found that the chip formed were saw tooth, continuous or semi-continuous chips (Fig.2).

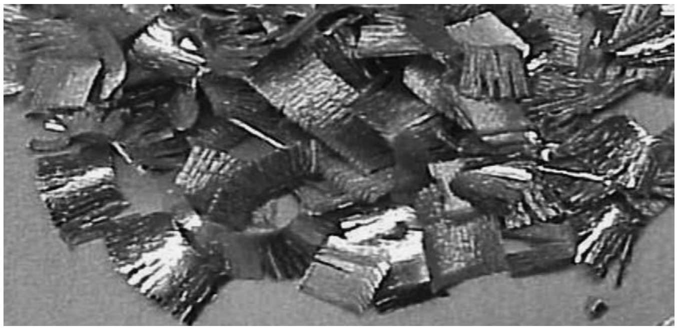


Fig-2: Serrated, semi-continuous chips formed [18].

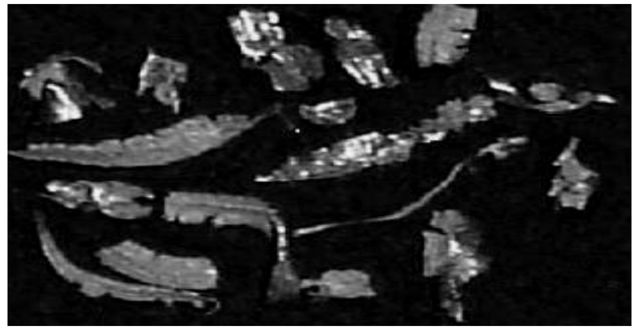


Fig-3: Chip formed by coated carbide drill [21].

M. SARAVANAKUMAR et. al. [19] studied the effect of dry machining of magnesium matrix composite using Tungsten coated carbide (K10) cutting tool inserts (TNMG 120404). Hence, the chip formation is tending toward to be more fragments due to the brittleness and the chips were short in length. As well, by the addition of (5%) graphite raises the brittleness of the matrix, that leads to which the chips are short in length [19]. The reduction in ductility of the metal matrix by adding of (SiC) particles aids, to generate a semi-continuous type of chip during machining [20]. Fig.3 shows the chip produced by drilling (Al/15%SiC/4%Gr) by coated carbide, the chip is short in length, discontinuous and sequence of chip segments is linked to each other [21].

4 Wear Mechanisms and Tool Life:

Cutting tool wear can defined as the undesirable removal of tool's material from the cutting edges leading to undesirable changes in the tool geometries [16]. The major cause of tool wear in the machining of MMCs is the straight contact between the nature abrasive reinforcement particles and the tool edges [3,6]. According to W. PEDERSEN et. al. [18], the main wear mechanism was abrasion when using (PVD) (TiCN/TiN) coated (C2) carbide inserts (TPG-322) cutting tool for machining (ZK60A-T5) magnesium matrix with the maximum wear on the flank face of the tool (Fig.4 and 5).

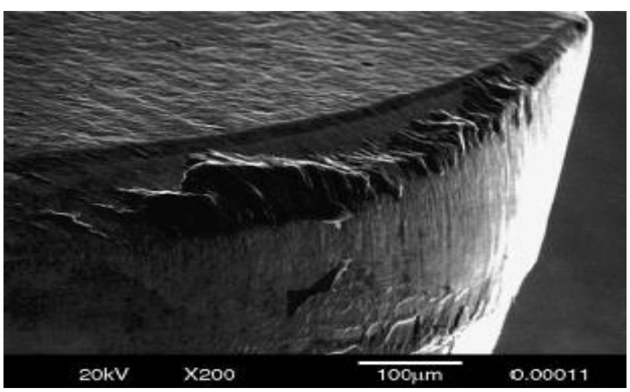


Fig-4: Cutting edge after 389m of cutting distance [18].

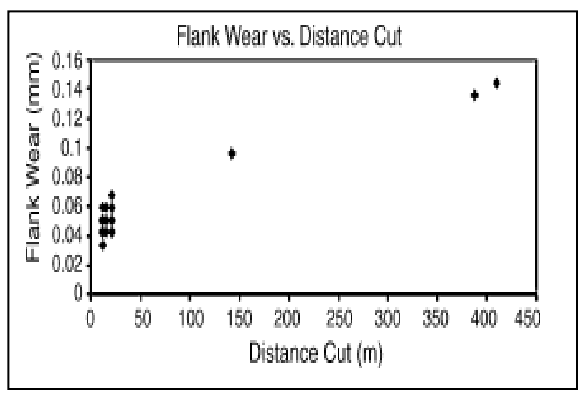


Fig-5: Flank wears vs. cutting length [18].

A. TASKESEN et. al. [22], conducted a drilling process using three types of drills materials (HSS, uncoated carbide and TiAlN coated carbide) for (B_4C) reinforced Al-alloy. According to this work-study, the most dominant tool wear mechanism was abrasive wear, and the flank wear growing from the cutting edge over the flank surface caused by the nature abrasive effect of B_4C particles (Fig.6).

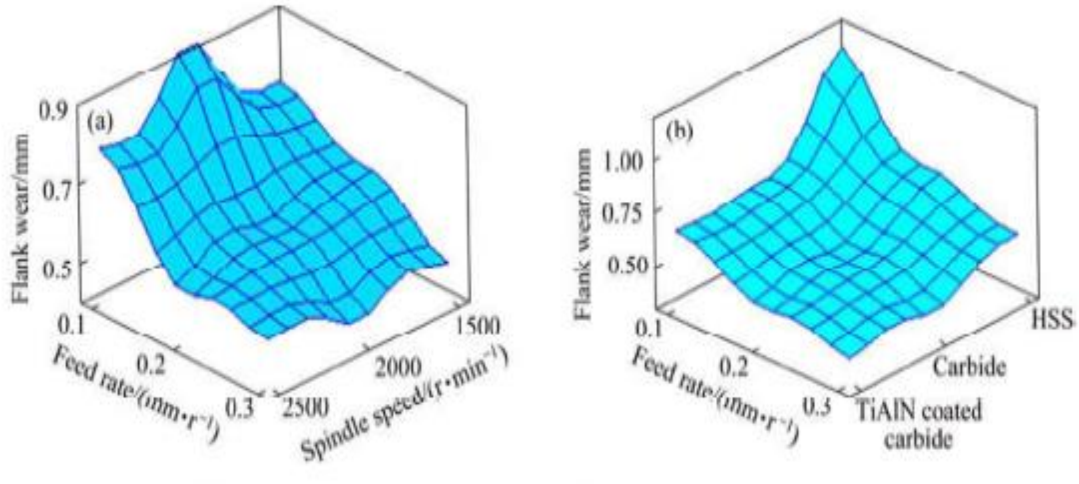


Fig-6: Effects of process parameters on flank wear (a) feed and speed, (b) feed and cutting tool [22].

Experimental work has done by XINLIANG WEI et. al. [23], using (MU7025) carbide and (PC750 PCD) tool inserts for machining (AZ91D) magnesium alloy reinforced with carbon fiber (CF). The wear modes of carbide tool were classified into the abrasive wear, adhesive wear and micro-breakage on the tool cutting edge. The wear modes of (PCD) tool were micro-breakage, abrasive wear. PCD tool offered a higher wear stability and resistance compare with the carbide tool (Fig.7).

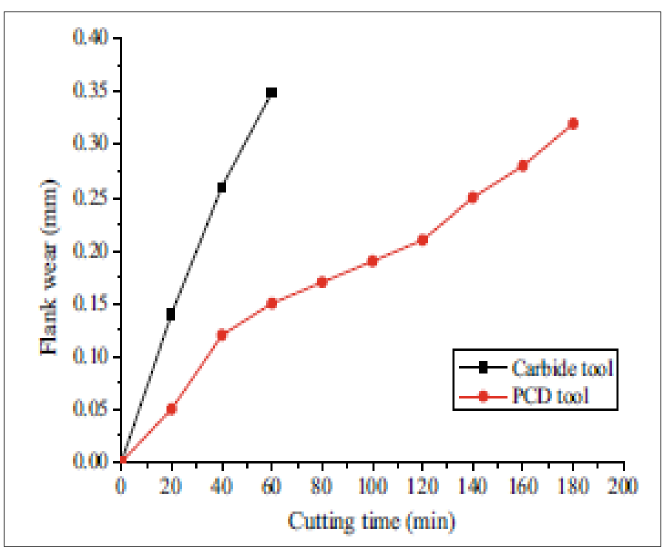


Fig-7: Relation curves of VB (max) with cutting time [23].

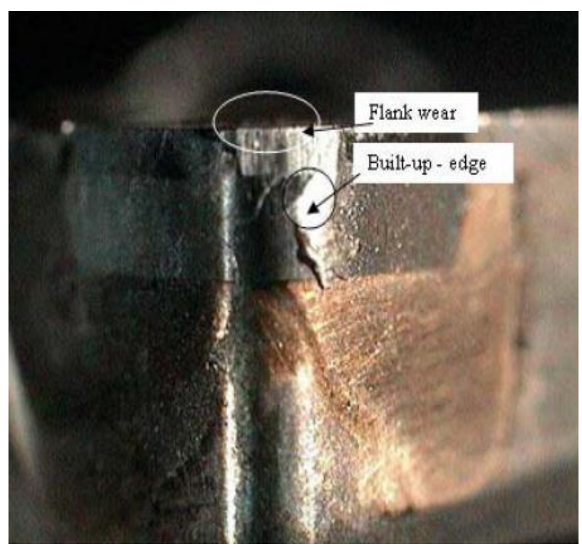


Fig-8: Flank wears of PCD tool [26].

The predominant wear mode in the drilling process of (MMCs) with (SiC) reinforced is progressed in the flank face of the tool, the abrasive wear mode is dominant, furthermore, some adhesions are observed [23,24]. Magnesium based composite (MMC) reinforced with (1.98 vol. %) of nano sized of (Ti) and (TiB_2) has been machined by (AlTiN) coated tungsten carbide obtained that the both of abrasion and adhesion wear mechanisms were observed. As well, it found that the chip adhesion influence was to be more obvious during machining with (Ti) particles comparing with (TiB_2) particles, because of the ductility of matrix metal Magnesium and reinforcement particles (Ti) [25]. According to [26] the wear on the (PCD) tool was caused by the abrasive manner of the (SiC) particles. (PCD) tools are harder than (SiCp), and the abrasive wear may be related to micro mechanical damage instead of micro cutting (Fig.8) [26]. S. BASAVARAJAPPA [27] conducted machining of (Al2219/15SiC-3Gr) and (Al2219/15SiC) using three types of cutting insert carbide (TCMT 1102), coated carbide (TCGX 1102) and PCD (TCMW 11020), the flank wear for all tools is more less when machining of (Al2219/15SiC-3Gr). This is because of thin lubricating film, which formed by the existence of graphite (Fig.9) [27].

5 Influence of Machining Parameters:

The optimization of machining parameters is the key to maximizing the efficiency and sustainability of MMCs machining processes [28]. Optimization of machining parameters leads to economical, sustainable and more efficient machining process [16, 28].

5.1 Effect of Feed Rate:

Feed rate has a significant effect on surface finish, high cutting speed and low feed rate resulted preferable surface finish and vice versa, those observed during study the effect of dry machining of magnesium matrix composite using Tungsten coated carbide (K10) cutting tool inserts (TNMG 120404), which has done by M. SARAVANAKUMAR et. al. [19]. In addition, when feed rate is increased, the cutting force increases, this because the increasing in contact area between the tool and the composite. It found that the feed rate factor has a significant effect on thrust and surface roughness [21,25,29]. According to [22], flank wear decreases as the feed rates increases (Fig.10). Minimal feed rates lead to higher wear of the cutting tool, furthermore the surface finish of the drilled specimen's damages with increasing in the feed rate at a constant speed [24]. The surface finish of the machined specimen's harms with increasing feed rates and the best result of surface finish obtained when higher cutting speed meets with low feed rates [26].

The major factor that affects the thrust force in drilling of metal matrix composites is the feed rate. Thrust force varies with feed rate, also the burr formation, increase when the feed rate increasing [30,31,32]. The feed rate is the factor that strongly affects the surface finish in the drilling process of metal matrix composites [33]. The feed rate is the main parameter that affects the torque in the drilling operation of the metal matrix composites and increases the torque as the feed rate increases [34].

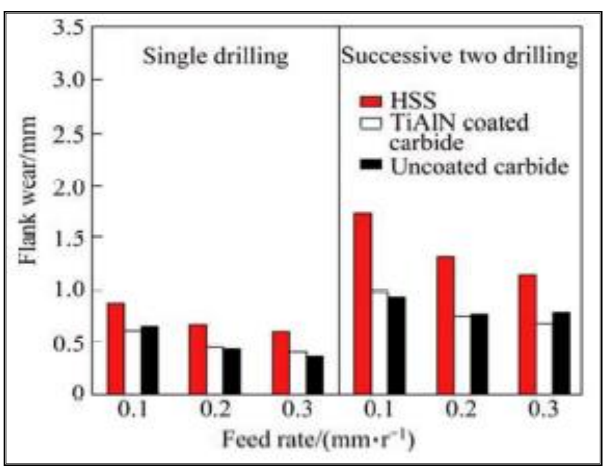


Fig-10: Flank wears of PCD tool [22].

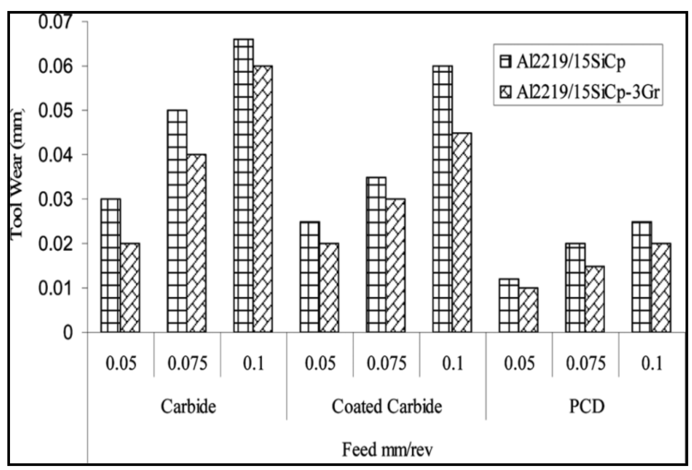
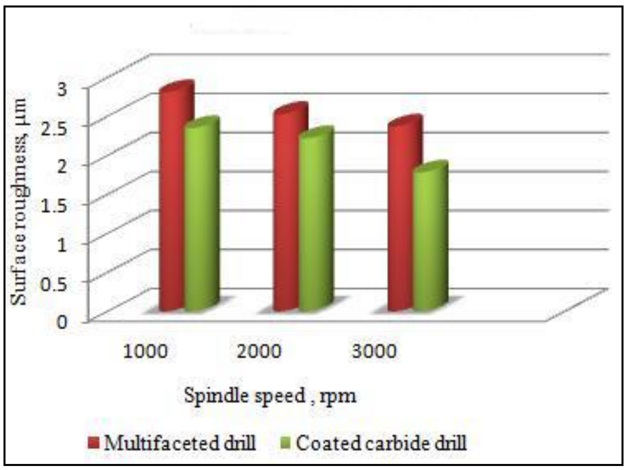


Fig-9: Tool wears vs. feed rate for various cutting tools [27].

5.2 Effect of Cutting Speed:

M. SARAVANAKUMAR et. al. [19] investigated the effects of dry machining of magnesium matrix composite using Tungsten coated carbide (K10) cutting tool inserts (TNMG 120404), by using ANOVA the analysis shown that the most important factor of surface roughness and cutting force is the cutting speed which contributes by (72.53%) and (79.11%) respectively, that the cutting force decreases when the cutting speed increases.

Investigations to evaluate the thrust force and surface finish in drilling process of (Al/SiC/Gr) hybrid metal matrix composite has done by A. MUNIARAJ et. al. [21], showed that thrust force is decreased with increasing of spindle speed and the surface roughness values has decreased with the increasing of spindle speed (Fig.11). The surface roughness, increases with increasing of both feed rate and rotation speed, and rotation speed has a significant effect on surface finish [25]. According to [26], decreasing of surface roughness and minimize of tool wear could be reached by using higher cutting speeds during machining of MMCs (Fig.12). Tool wear increases with the increasing in cutting speed and feed rate for all three types of cutting insert carbide (TCMT 1102), coated carbide (TCGX 1102) and PCD (TCMW 11020) using by S. BASAVARAJAPPA [19].



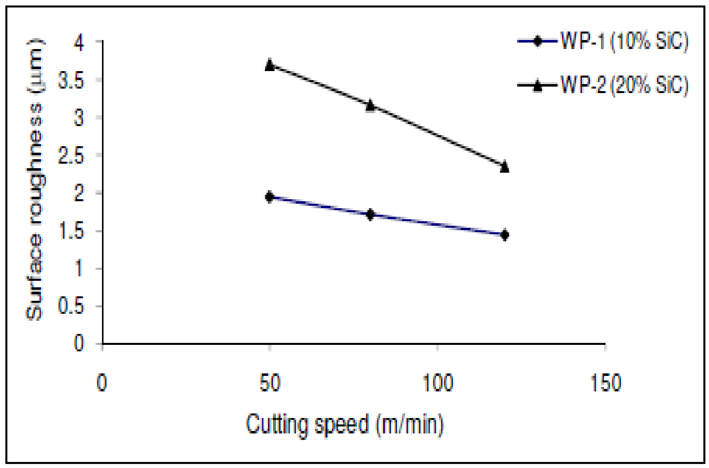


Fig-11: Spindle speed vs. surface roughness [21]. **Fig-12:** Cutting speed vs. surface roughness at f=0.1mm/r [26].

According to [30,31,32], during drilling process the thrust force decreases as the spindle speed increases, and vice versa, also lower spindle speed presents relatively more thrust force than higher spindle speed (Fig.13). The main influence parameter in respect of Torque during drilling process of (Al/15%SiC/4%Gr) hybrid metal matrix composites are the spindle speed, followed by feed rate [34]. In drilling experiment has done by J. PAULO DAVIM et. al. [35] by using (PCD) tools, showed that at constant cutting speed, the surface finish of the drilled samples decreases as the feed rate increases, but does not change significantly when changing cutting speed.

Fig.14 shows the machining force varies with the cutting speed which reported by [36] during orthogonal cutting of (Al/SiC) composites using titanium carbide (K10) insert tools, the tangential force decreases as the cutting speed increases, the reason for this reduction can be explained by reducing the thickness of the built up edge (BUE) when rising the cutting speed. Tool life is decreased with increasing of the cutting speed for all cutting conditions, a low cutting speed can recommended for the machining of coarse/particle/reinforced composites, and a high cutting speed can be applied for the machining of fine/particle/reinforced composites [3].

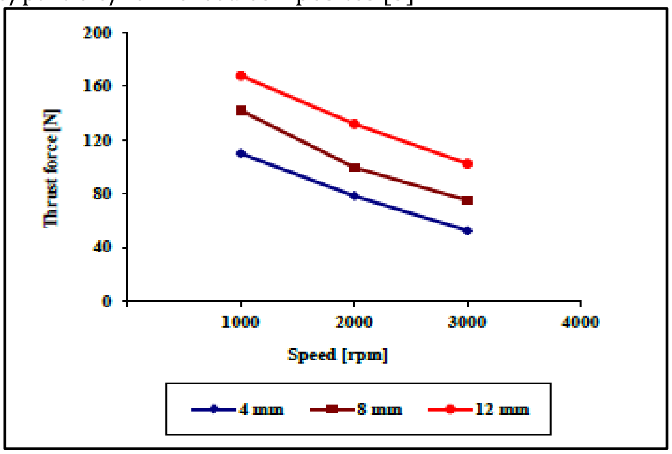


Fig-13: Thrust force with speed at different drill dia. [31].

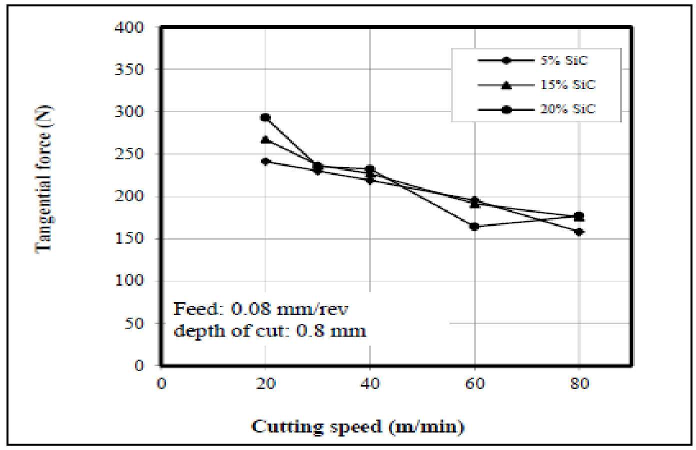


Fig-14: Tangential force vs. cutting speed [36].

6 Influence of Tool Material:

Machining processes of metal matrix composites (MMCs) with abrasive reinforcement's raises, the cost, tool wear and early failure of cutting tool [37]. Therefore, when machining (MMCs) tool chosen is essential important. Fig.15 presents the ranking of the cutting tool material kind used in the cutting processes for the experimental machining works surveyed during the review study has done by B. BOSWELL et. al. [28]. Fig.15 shows that most of the investigations for (MMCs) machining processes performed by using carbide or polycrystalline diamond (PCD) cutting tools. (CBN) and (PCD) tools are first and second orders of value better than carbide tools in terms of wear resistance, whereas carbide tools could be used economically for roughing machining [8]. When using a (PCD) tool, the reinforcement in the sub-surface area is usually almost clean without damages because the (PCD) tool cutting edge is very sharp. In the case of carbide tools, the reinforcement in the cutting sub-surface fractured because of plastic deformation [8]. W. PEDERSEN et. al. [18] have used a physical vapor deposition (PVD) (TiCN/TiN) coated (C2) carbide inserts to machine (ZK60A-T5) magnesium matrix with (20vol.% SiC) particles reinforcement, The (TiN) coating on the inserts is almost worn immediately upon start-up the machining, The coating is completely worn out within (20m) of cutting range. According to [21], in the improvement of surface finish, the coated carbide tool performance is better than multi-faceted carbide drill when machining (Al/15%SiC/4%Gr). An investigation conducted by XINLIANG WEI et. al. [23], using (MU7025) carbide and (PC750 PCD) tool inserts for machining (AZ91D) magnesium alloy reinforced with carbon fiber (Cf), recommended that (PCD) tool has higher wear resistance compared to carbide tools and is suitable for cutting (Cf / Mg) composites. XIANGYU TENG et. al. [25], used (AlTiN) coated tungsten carbide tool for machining magnesium-based (MMC) reinforced with nano sized (Ti) and (TiN). It is believed that the (AlTiN) coated carbide tool shows a high tendency to adhesive to the wok material during the cutting (Mg / Ti) MMC. In case of (Mg / TiB_2), the coating stripping ratio is more pronounced than that in the (Mg / Ti) peeled along the main edges.

Machining investigation work has conducted by S. BASAVARAJAPPA [27] of (Al2219/15SiC-3Gr) and (Al2219/15SiC) metal matrix composites using three types of cutting inserts, carbide (TCMT 1102), coated carbide (TCGX 1102) and PCD (TCMW 11020). For carbide tools, the flank wear is the highest, and less for (PCD) tool, as the length increases, the hard coat on the tool is peeling off due to impact action of the (SiC) particles; (Fig.16) shows the difference in the flank wear and cutting speed for all tools. (PCD) tools are superior to other tools in terms of tool wear resistance and they are recommended for mass production, and the coated carbide tools show flank wear less than of uncoated carbide tools [27]. From the experimental tests, obviously under different drill diameters, the surface roughness of the different cutting tools is similar. Compared with other drill tool materials, carbide twist drills have greater surface roughness in the drilling of hybrid metal matrix composites, the minimum surface roughness was observed for the step drill [33].

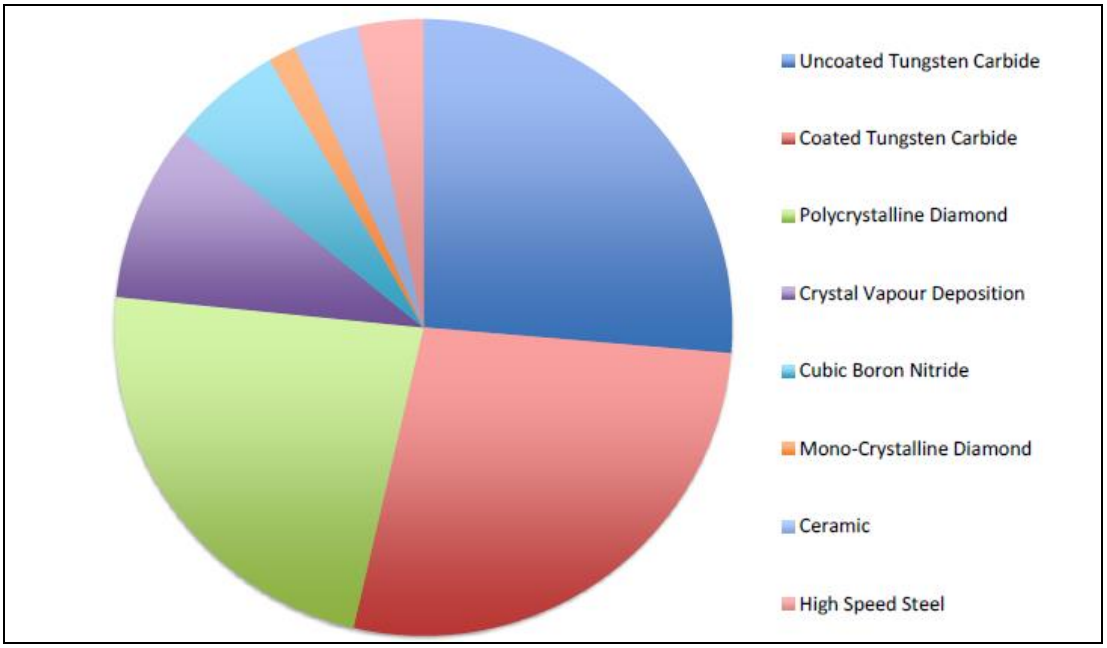


Fig-15: Tool materials used in the machining of MMCs [28].

(CBN) and (PCD) tools are first to second orders of magnitude better in wear resistance than (WC) tools. Although the (WC) tools can be used for roughing machining, (CBN) and (PCD) tools are used for finishing machining, because they can reduce sub-surface damage [38]. A study performed by M. S. SAID et, al. [39] has shown that under different cutting parameters, uncoated carbide drill bit exposures to less damage, followed by (TiN) coated carbide suffer the second least damage (Fig.16).

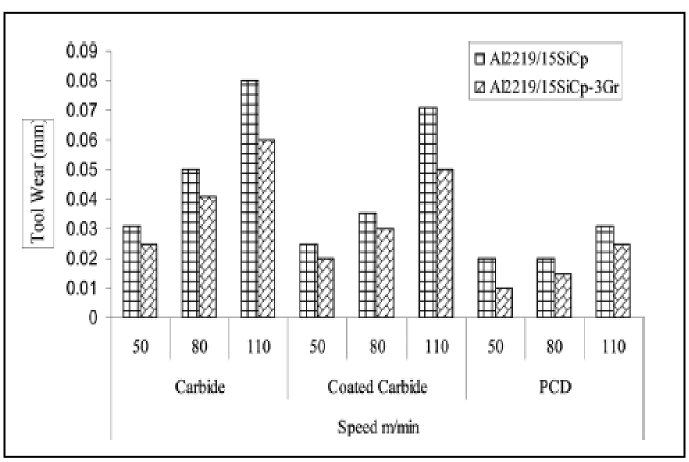


Fig-15: Tool wears vs. cutting speed for various tools [27].

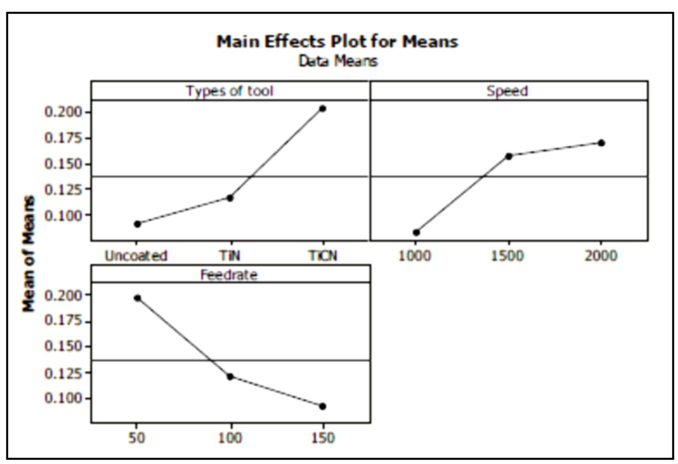


Fig-16: Main effects plot for means of tool wear [39].

7 Conclusion:

Nowadays, there is growing focus on MMCs reinforced with nano particles such as nano (SiC), carbon nano tubes (CNT) and graphene nano platelets (GNPs). Another effort is directed to investigate of hybrid composites, composed of varied matrix and (or) reinforcement materials. This paper briefly introduces the relevant research, focusing on the machining of magnesium matrix composites. For machining of magnesium based (MMCs), open literature reported only limited researches. Although, nearly all of the challenges of machining magnesium based composites are similar to which for aluminium-based composites. The machining of the (MMCs) is significantly different in many sides from the machining of monolithic metals and their alloys. During machining of (MMCs), their behavior is no homogeneous and anisotropic, and depends on the various reinforcement and matrix properties, and the content of reinforcement elements and the metal matrices. Thence, the mechanical properties change with the reinforcement format and allocation in the metal matrix specifies of chip formation mode (shearing, plowing and cracking) and then influence the machinability of (MMCs). The major wear in the machining of (MMCs) is the flank wear in the tool face. The abrasion is the major wear mechanism, and furthermore, slightly adhesions are observed. (CBN) tools are the first order of value superior in wear resistance followed by (PCD) tools in second order, than carbide tools. (PCD) tools are recommended for finishing operations because of their long tool life, while the carbide tool can be economically used for roughing operations.

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