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Advancements in Non-Conventional Machining of Aluminum Metal Matrix Composite materials

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Abstract: Aluminum Metal Matrix Composites (AMMCs) are new generation engineering materials that possess superior physical and mechanical properties compared to non-reinforced alloys. This makes them attractive for wider range of applications in automotive, aerospace and defense industries. The reinforcements in AMMCs are very hard and abrasive in nature. Thus, they pose a limitation to their economic conventional machining. Production of complex shapes in such materials by traditional methods is also difficult. In view of high tool wear and high cost of tooling with conventional machining, unconventional material removal processes offers an attractive alternative. Many unconventional machining processes, have found widespread applications in industry. The machining characterization of AMMCs material is necessary for high quality-cost effective product development. This paper presents a review of Non Conventional machining process and year wise research work done on AMMCs. The paper also discusses the future trend of research work in the same area.

Keywords: Metal matrix composite, Surface analysis, Machining

Introduction

Aluminum Metal Matrix Composites (AMMCs) are making in roads in various engineering applications requiring higher strength and stiffness than those offered by conventional aluminum alloys. Traditional machining of AMMCs however is difficult due to the hard reinforcement present in the AMMC material which tends to wrap around the cutting tool-bit leading to tool breakage. Over the past few years, there has been growing interest in non-conventional cutting of composite materials with regard to cutting rate, edge quality and the extend of damage incurred in the composite materials. Non-conventional machining has been applied on reinforced aluminum alloy. In these studies, specific machining performance characteristics on AMMCs reinforced with different percentage is assessed.

Classification and Processing of Aluminum based MMCs

Composite material is a material composed of two or more distinct phases (matrix phase and reinforcing phase) and having bulk properties significantly different from those of any of the constituents. The reinforcements can be in the form of continuous fibers, discontinuous fibers, particulates or whiskers. Continuous ceramic fibers and single-crystal ceramic whiskers are the reinforcements which provide the largest increases in strength and stiffness. Particulate-reinforced AMMC is driven by the combination of improved mechanical and physical properties imparted by the reinforcement of the metal matrix while still maintaining the favorable metalworking characteristics and predominantly metal-like behavior. A second significant driver is the ability to tailor the mechanical and physical properties through selection of the reinforcement composition and amount along with the matrix alloy. Figure 1 shows the type of non metallic and metallic reinforcements used in AMMCs.
The reinforcements are usually inorganic (ceramic) materials such as alumina, silicon carbide. Fiber materials used in AMMCs are graphite, aluminum oxide, silicon carbide, boron, molybdenum and tungsten. On the basis of Material Structure AMMCs are classified as follows:

Particulate Composites

Particulate Composites consist of a matrix reinforced by a dispersed phase in form of particles.

- Composites with random orientation of particles.
- Composites with preferred orientation of particles.

Dispersed phase of these materials consists of two-dimensional flat platelets (flakes), laid parallel to each other. Particulates are of silicon carbide, boron carbide.

Fibrous Composites

- *Short-fiber reinforced composites***.** Short-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of discontinuous fibers (length < 100 diameter).
  (i) Composites with random orientation of fibers.
  (ii) Composites with preferred orientation of fibers.
  Discontinuous fibers generally used are: alumina, alumina-silica.
- *Long-fiber reinforced composites***.** Long-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibers.
  (i) Unidirectional orientation of fibers.
  (ii) Bidirectional orientation of fibers (woven).
  Continuous fibers are in use: boron, silicon carbide, alumina, graphite.

Following are the processing methods of Al based MMCs:

- Solid State Processing
- Liquid state processing
- Powder Metallurgy
- Physical Vapor Processing (PVD)
- Direct Processing/Spray Deposition

Electric Discharge Machining

Electric Discharge Machining (EDM) is an electro-thermal non-conventional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive.

"Hung et al. (1994) investigated the feasibility of applying EDM process for cast aluminum MMCs reinforced with SiCp. Statistical models of the process were developed to predict the effect of process parameters on metal removal rate, re-cast layer, and surface finish. It was found that the SiC particles shield and protect the aluminum matrix from being vaporized, thus reduce the metal removal rate (MRR). The un-melted SiC particles drop out from the MMC together with surrounding molten aluminum droplets. While some aluminum droplets are flushed away by the dielectric, others trap the loosened SiC particles then re-solidify onto the surface to form a re-cast layer (RCL). No crack was found in the RCL and the softened heat-affected zone (HAZ), which was below the RCL. The input power controls the metal removal rate and the RCL depth, but the current alone dominates the surface finish of an EDM'ed surface". "Hocheng et al. (1997) presents the correlation between the major machining parameters, electrical current and on-time, and the crater size produced by a single spark for the representative material SiC/Al. The experimental results not only show the predicted proportionality based on heat conduction model, but are also compared with common steels regarding the material removal rate. For effective EDM, large electrical current and short on-time was recommended". "Yan et al. (1999) investigated EDM machining characteristics of Al_2O_3/6061Al composite using rotary electro-discharge machining with a tube electrode include peak currents, pulse durations, volume fraction of Al_2O_3 reinforced particles, flushing methods, flushing pressures and electrode rotations. Semi-empirical expressions for EDM-drilling were also developed to summarize the effect of machining characteristics such as the material removal rate, electrode wear rate and surface roughness. The peak currents of EDM-drilling and volume fraction of Al_2O_3 were confirmed to have significant affects on the MRR, EWR and surface roughness. In comparison, the flushing pressure and electrode rotation speed have minor affects on the MRR, electrode wear rate (RWR) and surface roughness (SR)". "Karthikeyan et al. (1999) developed mathematical models for optimizing EDM characteristics such as the MRR, the tool wear rate (TWR) and the surface roughness (CLA value). The process parameters taken in to consideration were the current, the pulse duration and the percent volume fraction of SiC (25 µm size) present in LM25 aluminum matrix. A three level full factorial design was chosen for experimentation and mathematical models with linear, quadratic and interactive effects of the parameters chosen were developed. The MRR was found to decrease with an increase in the percent volume of SiC, whereas the TWR and the surface roughness increase with an increase in the volume of SiC".

"Wang and Yan (2000) optimize the blind-hole drilling of Al_2O_3/6061Al composite using rotary EDM by using Taguchi methodology. Experimental results confirm that the revised copper electrode with an eccentric through-hole has the optimum performance for machining from various aspects. Three observed values, MRR, EWR, and SR, verify this optimization of the machining technique". "Ramulu et al. (2001) investigated the effects of EDM machining on the surface quality and subsequent performance of a 15 vol% SiC particulate reinforced A356 Al under monotonic and fatigue loading conditions. Surface and subsurface conditions after EDM surface sparking of the material were compared with the same material after careful surface polishing. Tensile tests were performed on the as-received material and the EDM surface sparked material to ascertain effects of EDM processing on basic monotonic properties. High cycle constant stress amplitude fatigue tests were conducted on the polished material and on the sparked material, and fractographic analysis was performed to study the mechanisms of fatigue fracture. EDM sparking was found to dramatically increase surface roughness and cause slight subsurface softening in the microstructure below the outer recast layer. Fatigue strength is notably reduced by EDM processing, with greater degradation resulting from higher MRR". "Mohan et al. (2004) investigated the machining characteristics of SiC/6025 Al composite using rotary EDM with a Brass tube electrode. Increase in volume percentage of SiC resulted in decrease in MRR and increase in EWR. The pulse duration had an inverse effect with MRR, EWR and SR. The decrease in the hole diameter and increase in speed of the rotating tube electrode resulted in increase in MRR and decrease in EWR and SR. In comparison, the electrode hole diameter and rotational speed have major effect on MRR, EWR and SR. The optimum machining parameter for maximum MRR, minimum EWR and better surface roughness were found out using genetic algorithm". "(Singh et al. 2004a and Singh et al. 2004b) investigated the effect of current Pulse ON-time and flushing pressure on MRR, TWR, ROC, and SR on machining as-cast Al-MMC with 10% SiC_P reinforcement. An L_{27} orthogonal array (OA), for the three machining parameters at three levels each, was opted to conduct the experiments. The experiments were performed in a random order with three successive trials. ANOVA was performed and the optimal levels for maximizing the responses were established. SEM analysis was done to study the surface characteristics. Also performed the optimization of the process on electric discharge machining of Al–10%SiCP as cast metal matrix composites using OA with Grey relational analysis by selecting the optimal levels of process". "Kansal et al. (2006) carried out an experimental study of the machining parameters in powder mixed electric discharge machining of Al–10%SiCp metal matrix composites and observed that MRR increased considerably with an increase in peak current for any value of pulse duration. The SR increased with increase in peak current and pulse duration".

"Seo et al. (2006) observed that in EDM machining of functionally graded 15–35 vol% SiCp/Al composites, the MRR increased with increasing current and pulse-on-time up to the optimal points and dropped drastically thereafter. Higher peak current and/or pulse-on-time resulted in both the greater tool wear and the larger average diameter error". "Dhar et al. (2007) evaluates the effect of current, pulse-on time and air gap voltage on MRR, TWR, radial over cut on EDM machining of Al–4Cu–6Si alloy–10 wt. % SiC_P composites using a cylindrical brass electrode of 30mm diameter. Three factors, three levels full factorial design was adopted for analyzing the results. A second order, non-linear mathematical model has been developed for establishing the relationship among machining parameters. ANOVA has been performed to verify the fit and adequacy of the developed mathematical models". "Dvivedi et al. (2008) investigated the machinability of Al6063 SiCp (developed using melt stir-squeeze-quench casting) metal matrix composite and obtained optimal setting of process parameters. The research work is related to influence of process parameters on performance measures and parameter optimization, the process variable affecting material removal rate according to relative importance are pulse current, pulse offsetting, flushing pressure, pulse on and gap control setting. The optimum value of these parameters was determined by experimentation". "Cichosz and Karolczak (2008) presented results of EDM machining of AMMCs with particular attention given to thickness of the defected layer after machining. Influence of various machining parameters on the behavior of saffil fibers and matrix material in the affected zone is presented. Scanning micrographs and roughness measurements are used to analyze surface finish. The influence of used current parameters on the quality of surface layer after electrical discharge machining was discussed. The results for composite materials are compared with those for aluminum alloys". "Ahmad et al. (2009) explores the possibility of machining using EDM machining by varying various machining parameters. Results indicated that AMMCs can be effectively EDM machined at low peak current at certain ON-time and OFF-time". "Kathiresan and Sornakumar (2010) developed aluminum alloy-silicon carbide composites using a new combination of vortex method and pressure die casting technique. Studies were conducted on the aluminum alloy-silicon carbide composite work piece using a copper electrode in an EDM. The MRR and SR of the work piece increases with an increase in the current. The MRR decreases with increase in the percent weight of silicon carbide. The surface finish of the machined work piece improves with percent weight of silicon carbide". "Iosub et al. (2010) studied the influence of the most relevant parameters of EDM Machining over MRR, electrode wear and machined surface quality of a hybrid metal matrix composite material (Al/SiC). The material used in this study is aluminum matrix composite reinforced with 7 % SiC and 3.5 % graphite. The hybrid composite was machined using brass tools with Ø = 3.97 mm. Different pulse on-times (ton), pulse off time (Toff) and peak current values (Ip) was used for each electrode. For the experiments, a full factorial design was used. Regression analysis was applied for developing a mathematical model".

Zhao et al. (2010) machined SiCp/Al using micro-EDM. First, a Φ40μm × 4.1mm micro tool electrode of which the aspect ratio is up to 100 was made; and then, through experiment, the impact of open-circuit voltage and electrode material on processing speed and electrode wear was analyzed; finally, 28μm wide micro slits, micro square platform of 34μm long on each side and other micro three-dimensional structure were machined. Research and experimental results show that the use of appropriate micro-machining parameters and reasonable processing methods can improve processing performance to better achieve the micro-EDM of SiCp /Al". "Singh et al. (2010) reported the work on EDM with SiC abrasive powder-mixed dielectric, a hybrid process. The machining of 6061Al/Al_2O_3p/20p work specimens has been carried out with copper electrode. An L_{18} orthogonal array was employed for the optimization of the performance measures such as MRR and SR. The effects of seven control factors (three levels each) and a noise factor (two level), and one two-variable interactions on the responses were quantitatively evaluated by the Length's method. Analyzed results indicate that the process effectively improves the MRR and reduces the surface roughness, in comparison with the conventional EDM". "Senthilkumar et al. (2011) investigated the effect of current, Pulse On-Time and flushing pressure on MRR, TWR during electrical discharge machining of as-sintered AMMC with 5% and 2.5% TiC reinforcement. An L_{18} orthogonal array, for the three machining parameters at three levels each, was opted to conduct the experiments. An attempt was also made to study the effect of TiC particle addition on the EWR, a new parameter taking into consideration both MRR and TWR. SEM analysis was conducted to study the recast layer evolved during the EDM machining process". "Nanimina et al. (2011) results indicate that 30% Al_2O_3 reinforced aluminum metal matrix composite can be machined using EDM to obtain acceptable result in terms of MRR and TWR. A high value of peak current and ON-time increase rapidly MRR of Al 6061 rather than AMMC while it decreases with increasing of OFF-time. Tool wears more at low peak current and ON-time than OFF-time".

Wire Electrical Discharge Machining

Wire electrical discharge machining (WEDM), a process variant of electrical discharge machining (EDM), is a non-traditional machining method that is widely used to pattern tool steels for die manufacturing. In the WEDM process, a small wire is engaged as the tool electrode. The dielectric medium is usually de-mineralized water. The work piece mounted on the table of the machine and the dielectric medium is ejected to the sparking area. The movement of the wire is controlled numerically to achieve the desired complex two and three-dimensional shapes for the work piece. WEDM uses electro-thermal mechanism to cut electrically conductive material. The material is removed by a series of discrete discharges between the wire electrode and the work piece in the presence of a dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The region in which discharge occurs is heated to extremely high temperatures, so that the work surface is melted and removed. The dielectric then flushes away the debris.

"Gatto and Iuliano (1997) describe WEDM tests performed under one roughing and two finishing conditions on two composites, SiC/2009Al alloy with 15% whiskers and with 20% particles reinforcement. Some roughed and some finished surfaces were glass-bead peened. To understand the reinforcement and the behavior of the matrix during the machining of both composites, the machined surfaces, their sections and profiles were examined by SEM, and energy dispersive semi-quantitative analyses of X-rays were also carried out". Rozenek et al. (2001) investigated the effect of machining parameters (discharge current, pulse-on time, pulse-off time, voltage) on the machining feed rate and surface roughness during WEDM of metal matrix composite AlSi7Mg/SiC and AlSi7Mg/Al_2O_3. Generally, the machining characteristics of WEDM metal matrix composites are similar to those which occur in the base material (AlSi7Mg aluminum alloy). The machining feed rate of WEDM cutting composites significantly depends on the kind of reinforcement. The maximum cutting speed of AlSi7Mg/SiC and AlSi7Mg/Al_2O_3 composites are approximately 3 times and 6.5 times lower than the cutting speed of aluminum alloy, respectively". "Yan et al. (2005) comprehensively investigated into the locations of the broken wire and the reason of wire breaking in machining Al_2O_3p/6061Al composite using WEDM. The experimental results indicate that the cutting speed (MRR), the surface roughness and the width of the slit of cutting test material significantly depend on volume fraction of reinforcement. Furthermore, bands on the machined surface for cutting 20 vol.% Al_2O_3p/6061Al composite are easily formed, basically due to some embedded reinforcing Al_2O_3 particles on the surface of 6061 aluminum matrix, interrupt the machining process. Test results reveal that in machining Al_2O_3p/6061Al composites a very low wire tension, a high flushing rate and a high wire speed are required to prevent wire breakage; an appropriate servo voltage, a short pulse-on time, and a short pulse-off time, which are normally associated with a high cutting speed, have little effect on the surface roughness". "Manna and Bhattacharyya (2006) determined the parameters setting during the machining of aluminum-reinforced silicon carbide AMMC. The Taguchi method was used to optimize the CNC-wire cut-EDM parameters. According to the Taguchi quality design Concept, a L_{18} mixed orthogonal array was used. From experimental results and through ANOVA and F-test values, the significant factors are determined for each machining performance criteria, such as the MRR, SR, gap current and spark gap (gap width). Mathematical models relating to the machining performance are established using the Gauss elimination method for the effective machining of Al/SiC-MMC". "Patil and Brahmankar (2006) investigated the performance of Al/SiCp composites with WEDM. Taguchi method was used for experimental design. Based on experimental results, mathematical models relating the Machining performance and machining parameters were developed. Optimal settings for each performance measure have also been investigated. A comparative study on unreinforced alloy revealed the effect of reinforcement. Cutting speed for unreinforced alloy was found higher compared to composites. But surface finish in composites was found superior compared to the unreinforced alloy. Wire breakage posed limitations on the cutting speed of composite". "Satishkumar et al. (2011) investigated the effect of WEDM machining parameters such as pulse-on time, pulse-off time, gap voltage and wire feed on MRR and SR in AMMCs consisting of aluminum alloy (Al6063) and SiCp. The Al6063 is reinforced with SiCp in the form of particles with 5%, 10% and 15% volume fractions. The experiments were carried out as per design of experiments approach using L_9 orthogonal array. There results were analyzed using analysis of variance and response graphs. The results were also compared with the results obtained for unreinforced Al6063. From this study, it was found that different combinations of WEDM process parameters are required to achieve higher MRR and lower Ra for Al6063 and composites. Generally, it was found that the increase in volume percentage of SiC resulted in decreased MRR and increased Ra. Regression equations were developed based on the experimental data for the prediction of output parameters for Al6063 and composites".

Electrochemical Machining (ECM)

ECM is opposite of electrochemical or galvanic coating or deposition process. Thus ECM can be thought of a controlled anodic dissolution at atomic level of the work piece that is electrically conductive by a shaped tool due to flow of high current at relatively low potential difference through an electrolyte which is quite often water based neutral salt solution. During ECM, there will be reactions occurring at the electrodes i.e. at the anode or work piece and at the cathode or the tool within the electrolyte. MRR is an important characteristic to evaluate efficiency of a non-traditional machining process. In ECM, material removal takes place due to atomic dissolution of work material.

"Goswami et al. (2009) presents electrochemical grinding of Al_2O_3/Al interpenetrating phase composite. The effect of electrolyte concentration, supply voltage, depth of cut, and electrolyte flow rate on machining performances has been studied. The characteristic features of the electrochemical grinding (ECG) process are explored through Taguchi-design-based experimental studies with various process parametric combinations and finally the process has been optimized. The mechanism of material removal and surface characteristics under different grinding conditions have been studied through SEM micrograph. Besides, another set of experimental investigation has been carried out in order to identify the influence of different type of electrolytes and degree of reduction in grinding force in ECG. Finally, a comparative study of conventional and electrochemical grinding of this special class of material has been carried out". "Senthilkumar et al. (2009) investigated the influence of some predominant electrochemical process parameters such as applied voltage, electrolyte concentration, electrolyte flow rate and tool feed rate on the MRR and SR to fulfill the effective utilization of electrochemical machining of LM25 Al/10%SiC composites produced through stir casting. The contour plots are generated to study the effect of process parameters as well as their interactions. The process parameters are optimized based on Response Surface Methodology (RSM). "Santhilkumar et al. (2009) machined the A356/SiCp composite work material using Electro Chemical Machining process.

Taguchi's L_{27} orthogonal array is chosen to design the experiments and 54 trials are conducted to study the effect of various parameters like applied voltage, electrolyte concentration, feed rate and percentage reinforcement on maximizing the material removal rate. A mathematical model is also developed using the regression method.

Abrasive Water Jet Machining (AWJM)

In the abrasive water jet, the water jet stream accelerates abrasive particles and those particles erode the material. In AWJM, abrasive particles like sand (SiO_2), glass beads are added to the water jet to enhance its cutting ability by many folds. In AWJM, the abrasive particles are allowed to entrain in water jet to form abrasive water jet with significant velocity of 800 m/s. Such high velocity abrasive jet can machine almost any material".

"Savrun and Taya (1988) investigated the machinability of two classes of high-temperature composites (SiC whisker/2124 aluminum and SiC whisker/Al_2O_3) with an AWJM. The machined surfaces of the composites were characterized by SEM, energy dispersive X-ray spectroscopy and profilometry to determine the surface finish. Micro hardness measurements were also performed on the machined AMMCs. AWJM appears to be a quite promising machining method due to its fast speed and economical operation. It gives relatively smooth surfaces coupled with minimum subsurface micro structural damage".

Comparison of non-conventional machining processes

"Muller and Monaghan (2000) present details and results of an investigation into the machinability of SiC particle reinforced aluminum matrix composites using non-conventional machining processes such as EDM, laser cutting and AWJM. The surface integrity of the composite material for these different machining processes are examined and compared. The influence of the ceramic particle reinforcement on the machining process was analyzed". "Muller and Monaghan (2001) investigated into the machinability of silicon carbide particle reinforced aluminum alloy matrix composites using non-conventional machining processes such as EDM and laser cutting. The different removal mechanisms of the different processes when machining the composite were investigated. The surface condition and sub-surface damage of the material for the different machining processes have been examined and compared. It appears that both EDM and laser are suitable processes for machining AMMCs, Laser offers significant advantages in terms of removal rate. EDM however induce less thermal damage than that was observed using the laser. Liu et al. (2009) studied the behavior of wire electrochemical discharge machining of Al_2O_3 article reinforced aluminum alloy 6061. The relative strength of the WEDM and ECM activities in the machining process under different conditions was investigated with the aid of the voltage waveforms. In this paper, authors compared two types of machining processes with same material. Only material removal rate is considered as performance measures.

8. Discussion and future trends

After an elaborate scrutiny of the published work, the following conclusions can be drawn:

- More work has been carried out on AMMCs using EDM. However few references were found regarding other non conventional machining of AMMCs. Thus it is imperative to study comprehensively in terms of process parameters of other non conventional machining methods for machining AMMCs.
- It has been a problem area for researcher to obtained optimal and economical performance of Non conventional manufacturing process. Thus extensive examination is needed to obtain optimal setting of different machining parameters.
- Lesser work has been reported on theoretical models for simulating the input and output parameters for AMMCs on Non conventional manufacturing processes. Much research work is needed in this area.
- Mostly SiC particulate have been tried in composites, a few work on Al_2O_3 particulate has been reported. The choice of Silicon carbide as the reinforcement in aluminum composites is primarily due to its excellent combination of physical properties, availability and cost.
- No paper has reported in change of properties of surface material after non conventional machining on AMMCs.
- Many AMMCs are yet to be explored for suitable machining and process parameter design since very little research work has been reported in these areas. No much work has been done on Aluminum Matrix Composites Reinforced with Si3N4, AlN and ZrB2, SiO2, B, BN, B_4C, may also be considered in future.
- The application of lower cost reinforcement materials is also an important R&D area.
- Some fundamental mechanisms use are still not understood in machining of AMMCs:
  - what is the influence of constituent properties?
  - what is the effect of particle size, shape and distribution?

There is clear scope for improvements in the properties of reinforcements. Substantial advances in fibers for AMMCs have been achieved in terms of strength, for example, the performance of alumina fiber-reinforced in aluminum matrix has doubled over the past decade. Recent work has also shown that significant differences exist between ceramic particles that can be used as reinforcements for aluminum matrix. Research on the economical production of high strength, low-cost, ceramics for the reinforcement of metals would be very important. Machining operations are challenging when applied to AMMCs. Research in this area is critical for certain applications of these materials. Systematic investigations are required of the fundamental links between microstructure and properties. Table.1 shows the progress of research work on machining of AMMCs year wise.

Conclusion

A review of the research work on AMMCs with non-conventional machining is presented in this paper. The research work of the last 20 years has been discussed. Of the many of non-traditional machining methods reviewed in this article, EDM is currently used extensively in industry for machining of AMMCs. This is reflected in the number of publications concerned with these processes. For each and every method introduced and employed in machining process, the objectives are the same: to enhance the capability of machining performance i.e. more material removal rate and better surface finish and to get better output product.

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Advancements in Non-Conventional Machining of Aluminum Metal Matrix Composite materials

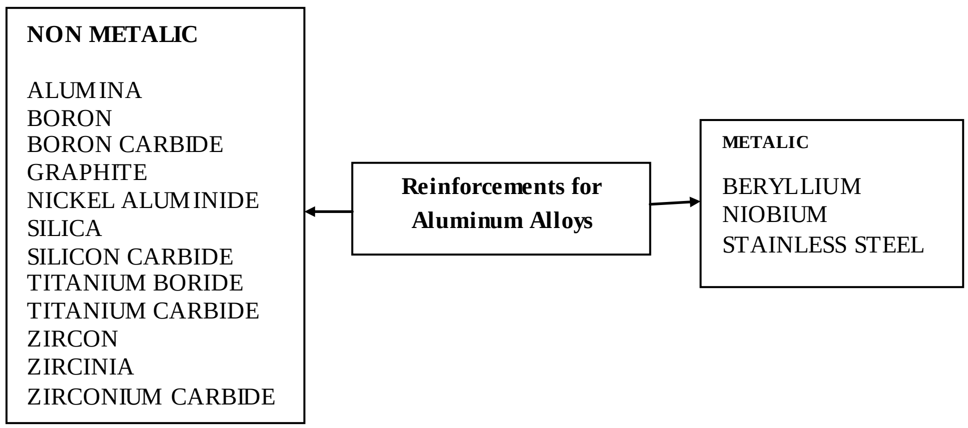

Figure 1. Type of reinforcements used in AMMCs

Advancements in Non-Conventional Machining of Aluminum Metal Matrix Composite materials

Table No. 1. Progress in non-conventional machining of AMMCs

Year	Machining	Author	Aluminum composite	Output parameter
1988	AWJM	Savrun et al.	SiC whisker/2124 Al/Al_2O_3	Surface finish

1994	EDM	Hung et al.	SiC/Al	MRR,TWR.SR
1997	WEDM	Gatto et al.	SiC/2009Al,	Surface quality
1997	EDM	Hocheng et al.	SiC/Al	MRR,TWR.SR
1999	EDM	Biing Hwa Yan et al.	Al_2O_3/6061Al	MRR,TWR.SR
1999	EDM	Karthikeyan et al.	SiC/Al	MRR,TWR.SR, Mathematical models
2000	EDM	Wang et al.	Al_2O_3/6061Al	MRR, EWR, and SR
2000	EDM, laser cutting , AWJM	Muller et al.	SiC/Al	Surface integrity
2001	WEDM	Rozenek et al.	AlSi7Mg/SiC and AlSi7Mg /Al_2O_3	Optimum Cutting speed
2001	EDM	Ramulu et al.	SiC/A356 Al	Surface quality
2004	EDM	Mohan et al.	SiC/6025 Al	MRR, EWR, and SR
2004	EDM	Narender Singh et al.	Al–10%SiC_P	Machinability
2005	WEDM	Biing Hwa Yan et al.	Al_2O_3p/6061Al	Cutting speed, SR
2006	EDM	Kansal et al.	Al–10%SiC_P	MRR, SR
2006	EDM	Seo et al.	15–35 vol% SiCp/Al	MRR
2006	WEDM	Manna et al.	Al/SiCp	MRR, SR, gap current, spark gap and Mathematical models
2006	WEDM	Patil et al.	Al/SiCp	Mathematical models, Cutting speed, SR
2007	EDM	Sushant Dhar et al.	Al–4Cu–6Si alloy–10 wt.% SiC_P	Second order, non-linear mathematical model
2008	EDM	Dvivedi et al.	Al6063/SiCp	Machinability
2008	EDM	Cichosz et al.	fibers of Al_2O_3 /Al	Surface integrity
2009	ECG	Goswami et al.	Al_2O_3/Al	MRR, SR
2009	ECM	Senthilkumar et al.	A356/SiCp	Mathematical model using the regression method
2009	WEDM, ECM	Liu et al.	Al_2O_3p/6061Al	MRR
2010	EDM	Adrian Iosub et al.	Al/SiC, 7 % SiC and 3.5 % graphite	MRR, SR
2010	Micro EDM	Zhao et al.	SiCp/Al	MRR, EWR.
2010	Powder EDM	Shankar Singh et al.	6061Al/Al_2O_3p/20p	MRR, SR
2011	EDM	Senthilkumar et	Al with 5% and 2.5% TiC	MRR, TWR.

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		al.		
2011	EDM	Nanimina et al.	Al_2O_3/6061Al	MRR, TWR.
2011	WEDM	Satishkumar et al.	Al6063/SiCp (5%, 10% & 15%)	MRR, SR

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