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Original article

Study And Analysis Of Wire Edm Process On Metal Matrix Composites

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Abstract: *Wire Edm is one of the most efficient and flexible non traditional machining process particularly suitable to the manufacturing of components of complex shape and close dimensional tolerances which cannot be produced by conventional machining. How it works: The procedure is based on electricity being discharged (in the form of sparks) from a pair of electrodes to the workpiece, and wire elecrtode by using a small gap maintained and pushing out the sparking zone to a contested workpiece. This unique capability has made WEDM one of the most widely-used machining processes for advanced materials such as Metal Matrix Composites (MMCs), which are being used in aerospace, automotive, defense and medical applications because of their superior strength to weight ratio, wear resistance and thermal stability. Its properties are inhomogeneous which include ductile metal matrix that contain hard ceramic particles or fibers and these materials presented challenges in machining. The shortage of hardness and thermal conductivities in the matrix phase and reinforced phase, generally, is considered as the sources of problems such as a broken wire, tool wear, fluctuated material removal rate and worsened surface quality.*

The objective of the present study is to investigate in a systematic way the effects of the WEDM machining parameters such as pulse-on time, pulse-off time, discharge current, wire tension, and dielectric pressure in machining of MMC's in terms of the machining performance. The importance of the process parameters on the critical output responses, MRR, Ra, kerf width and surface quality is emphasized in the study. Nobel designs, either that be Taguchi approach or Analysis of Variance are employed for identification of the most influencing factors and for establishing the optimal processing conditions for obtaining the maximum productivity of the process without losing its precision. Specifically, WEDM-induced microstructural features in the form of recast layers, micro-cracks, and changes in the heat-affected zone (HAZ) are focused on, that could influence the functional properties and fatigue life of the machined MMC.

The conventional machining methods are compared with WEDM with respect to the strength and material removal rate as well as the cost involved in machining hard and brittle MMCs and emeritus WEDM could machine high strength, hard and brittle MMC grades without imposing excessive mechanical stress, and the demeritus of the slower material removal rate and higher cost involved in its operation. The paper also includes a close look at mixed machining processes and recent improvements such as powder mixed dielectric fluids, covered wire electrode and adaptive control system that allegedly result in enhancements in productivity and surface finish of the products. Additionally, sustainability factors of dielectric fluid recycling, reducing energy consumption and more environmentally friendly manufacturing in accordance with the current trend of green manufacturing are also considered by the research.

The findings contribute to the theoretical research about the precision machining of advanced materials and indicate some suggestions of industry people and researchers for improving WEDM performance of MMCs. The paper also reveals the underlying physical mechanisms and identifies the optimal range of process parameters.The findings of this study are expected to play an important role in developing reliable, cost-effective, and environmentally-friendly next generation high performance component manufacturing processes. The findings obtained provide the glimmer of hope for further extending the WEDM capability for emergent composites and thus accelerate their wider applications in the extreme as well as critical service performance industries.

Keywords: *Wire EDM, Metal Matrix Composites, Electrical Discharge Machining, Surface Integrity, Material Removal Rate, Tool Wear, Machining Parameters, Advanced Manufacturing*

I. INTRODUCTION

The motivation of finding new high performance, lightweight yet stiffer engineering materials has been one of the great driving forces for the extensive utilization of Metal Matrix Composites (MMCs) in automotive, aerospace, medical and defence engineering. MMC is a material that consists of a metallic or metal alloy matrix whose properties are significantly improved due to the addition of ceramic particles, whiskers or fibers to the metal matrix giving it the ductility and toughness of the metals combined with the hardness, wear and thermal resistance of the ceramics. For example, these include aluminium matrix composites (AMCs), titanium based composites and magnesium composites reinforced with silicon carbide (SiC), alumina (Al_2O_3) or boron carbide (B_4C). These composites exhibit superior mechanical attributes including high specific strength, good wear resistance, and superior thermal conductivity that are suitable for demanding applications under hostile conditions. But, because they also possess these desirable features, MMCs are also notoriously tough to machine using conventional manufacturing processes.

Because MMCS has abrasive reinforcements, it is generally difficult to machine it by the conventional methods (turning, milling, drilling) due to severe tool wear, low machining accuracy, and poor surface finish. In addition, the large disparity between the thermal conductivities between the metal matrix and the reinforcing phase will lead to possible hot spots and consequentlyStress raising points which complicate the matter even further. To overcome these obstacles, unconventional machining processes such as Electrical Discharge Machining (EDM) and specifically Wire EDM (WEDM) are often used in machining of MMCs.

Wire EDM is a heat-electro process where material is REMOVED from the workpiece by a series of discrete electrical discharges (SUM OF ^ENERGY), we have the conditions of sparse flow of energy between spark and the workpiece, which is the result of small voltage duration value of discharge; these are the result of...flow of energy is Ampere and the voltage is Volt between what is wire and the workpiece (Workpiece-) Place into a hinchos fluid. Unlike in conventional machining, no mechanical contact was required during WEDM, resulting in no cutting force, no wear and therefore, no possible deformation of the fragile part, which might occur in the process. So it's perfect if you need to machine complex profiles, or to drill corrosive or abrasive materials, then the PCD allows for a very fast machining cycle. This is accomplished by closely controlled pulse-on and pulse-off time, discharge voltage, wire tension, feed rate, and dielectric pressure. Nevertheless, because of the heterogeneous distribution of MMCs, some specific problems should be overcomed in WEDM, such as uneven spark distribution, uneven material removal caused by dispersion of the reinforcing particles, and so on, which finally result in wire breaks and make it difficult to guarantee the optimal surface integrity.

Importance WEDM on MMCs Other hand is the trend of generating advanced materials and requirement to high precision composite parts with the guarantee of high precision mechanical and surface properties. Optimization of the process parameters is a key target in order to find an optimal compromise between a high productivity and a good surface quality and low defect content in shape of recast layer and micro-cracks, respectively large kerf width. Further, influence of WEDM process on microstructural and metallurgical behaviour of MMCs which determine their performance in long-term and reliability of the components under service conditions is of paramount interest.

The scope of the present work is to make a comprehensive review of the literature significant to the process of WEDM of MMCs including review of the process basics, problems, effect of process parameters, optimization methodology and performance comparison. By combining experimental evidence with current statistical and analytical tools, this investigation will provide the means for developing realistic machining guidelines that shop floor practitioners can apply towards more sustainable, accurate and productive shaping of forthcoming composites.

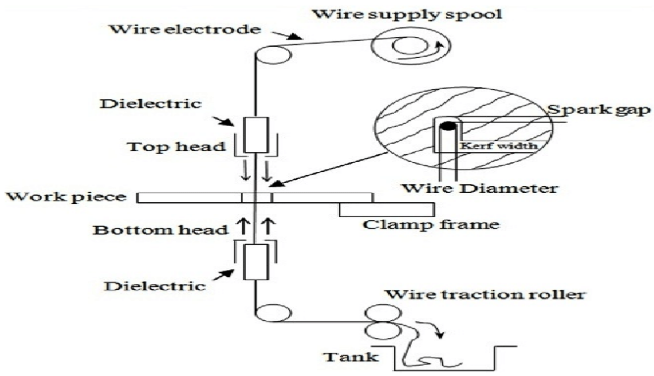

Figure1: Introduction

II. WIRE EDM THEORY AND OPERATION

Wire Electro Discharge Machining (WEDM) is a high precision non-conventional machining process and is developed from spark erosion principle. It is a process in which a shape is produced in a workpiece by successive controlled discharges, or sparks, from a wire electrode-the wire EDM (electric discharge machine) and the electrically conductive job-the workpiece, which are separated by a film of a dielectric fluid. WEDM is different from traditional cutting tools because it uses mechanical force to cut the workpiece, making it a potential method for cutting hard, brittle or brittle materials likes Metal Matrix Composites (MMCs).

Basic working principle of WEDM is that pulsating DC voltage is applied between the wire tool and the workpiece. If the gap between electrodes is short enough, the electric field amplitude exceeds the dielectric breakdown strength of the fluid, thus causing ionization. The ionization forms a plasma channel between the wire and the workpiece, and allows an electrical discharge to proceed in the form of a spark being the electrical discharge, for example a spark. There is thus formed an extremely high (8 000-12 000°C.) local temperature which causes a part of the discharged material to melt and to vaporize. The very instant that the discharge ceases, however, the dielectric fluid washes away the molten metal in finely divided form, and sets the thermal-insulating ability of the fluid available for another spark.

The wire electrode, usually brass, copper, tungsten, or zinc-coated brass, is pulled through a line tensioner to a supply spool, as above, or a version of a Relaxation Brake (which can also be used to draw it to its supply spool), and into the wire drive system. Since the electrode is always being pushed through the liner, the wire is continuously fed through the liner to the work piece in a manner that the relationship between the wire, nozzle, and work piece is maintained. And the uniform cutting performance will make it keep sharp little long. These are controlled by CNC and produce shapes, profiles, sharp inside corners and small hole radii with significant precision by following the wire. The cutting operation is non-contact (no stress in the workpiece) unlike conventional tools that would apply compression to a brittle or thin-walled MMC part.

WEDM PROCESS PARAMETERS The WEDM process is influenced by the parameters as mentioned below: Important Parameters to achieve higher efficiency and quality in WEDM: 1. Pulse-on time determines the duration of a single discharge, and has effects on MRR and surface roughness. Pulse-off time is to push body dirt to avoid a short circuit. Discharge voltage determine the energy and penetration depth of spark. The strain on the wire has to do with the precision of the cut, on the one hand with no vibration of the wire and on the other with no sawing of the wire. The utilization of dielectric fluid pressure is also a requirement for efficient debris removal, especially in MMCs since high-hardness reinforcement particles in the particles tend to obstruct the outflow.

WEDM has its own problems when used for MMCs. The metal matrix thereby has a much higher thermal conductivity as well as coefficients of thermal expansion than the ceramic reinforcements, giving rise to non-uniform material removal. Sparks may have a tendency to selectively remove the softer of the materials thereby partially or completely exposing the reinforcing particles and effecting the surface finish. To overcome these challenges the discharge energy, flushing conditions, and wire need to be optimized.

In other words, the principle of WEDM is to use the precision electric control combined with thermal energy to implement the high precision machining with complex outline. Moreover, due to its non-contact nature, versatility, and capability of machining even very hard or very fragile materials, LP has also been identified as a fundamental technology in the manufacturing of advanced MMC components for high demanding industries.

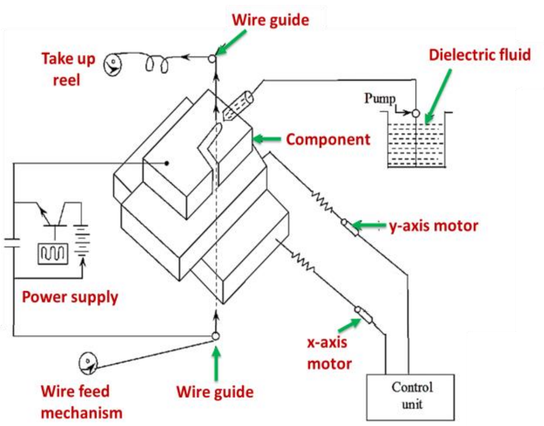

Figure 2 : Wire Edm Theory And Operation

III. FEATURES AND CHALLENGES OF MACHINING OF MMCS

Metal Matrix Composites (MMCs) are well known for their good mechanical performance, high thermal performance and wear resistance, and include a ductile metallic matrix, and hard reinforcement phases, for example, ceramics (e.g., SiC, Al2O3, B4C, TiC). The strength and ductility are primarily contributed by the matrix, including the aluminum/magnesium/titanium alloy matrix, and the hardness stiffness, wear resistance and thermal stability are primarily provided by the reinforcement. This fiber reinforced matrix architecture that has enabled MMC's to offer the high specific strength, the low thermal expansion and the excellent dimensional stability in high temperature, elevated temperature service condition, and is therefore ideally applicable for both aerospace, automotive, defense, and biomedical application.

While such properties are to be desired in a composite when it is being used, they present an enormous problem during the manufacturing of the composite, particularly when it being machined. The MMCs are inhomogeneous due to the obviously different hardness, melting point and thermal conductivities of matrix and reinforcement phases. The turning and milling and drilling etc. have a typically strong tool wear due to the abrasive ceramic reinforcement. The abrasive particles act like abrasive grains to scratch or wear the tool edge, whereby the tool should be changed frequently, and high production cost is incurred.

Another problem lies in the removal of non-uniform material. Soft matrix material in mechanical cutting is eroded faster than reinforcements, favoring production of a surface in which reinforcements may protrude above the machined plane. Not only will this have some sort of influence on surface gloss, but the level may be too low for the mechanical requirements of the component, especially in precision fits and sealing surfaces. Moreover, such the reinforcement particles would cause the hone of the cutting tool to be broken or the vibration for HSM would be occurred to deteriorate the dimensional precision of a product.

Thermal effects also pose problems. A temperature discontinuity is present between matrix and the reinforcement and localized heating is found in the machining. This can lead to thermal stresses, deformation and occasionally matrix softening or microstructural alteration, such as, over-aging in heat treatable alloys. In the worst instance these effects could create stresses or microcracks in the material and shorten the life of the component.

When MMC's are machined with WEDM, some of these problems are lessened, since the tool and workpiece do not come in direct physical contact. However, the inhomogeneity of MMCs still affects spark erosion. For example, metal matrix's wear resistance can be significantly better than the particles in case the reinforcement is a less electrically conductive particles, and this could result to an uneven kerf width and non-homogeneous distribution of sparks. These differences result in variations of surface roughness and an additional process might be required for achieving smooth texture. Macerian ceramic reinforcements, on the other hand, can also be the cause of wire electrode wear, for example when machining with thick section or when the flushing effect is not sufficient.

Debris is also a problem. Among (3) relatively stronger breakdown resistance that the reinforcing particles possess and their removal from the spark gap, are greatly dependent on the dielectric fluid flush. Poor flushing can lead to contaminate build up, shorting, cutting instability and lost time.

In general, with respect to MMC machining, whether used on the conventional or WEDM, careful optimisation of operating conditions and tool (or electrode) material selection, as well as flushing/cooling procedures is still necessary. The complex interplay between metal matrix and reinforcement must be considered to address these problems and enable a problem-free and economic production of high performance composite parts.

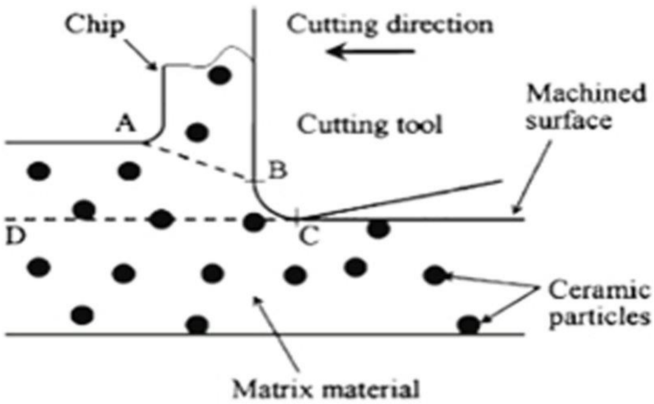

Figure 3: Features And Challenges Of Machining Of Mmcs

IV. IMPACT OF PROCESS PARAMETERS ON MACHINING PERFORMANCE

In WEDM, the parameters of the process which govern the machining performance are mainly the process parameters which are selected and controlled. These parameters influence several performance characteristics such as MRR (material removal rate), Ra (surface roughness), kerf width, dimensional accuracy and surface integrity. For Metal Matrix Composites (MMCs), the electrical and thermal properties are non-uniform, therefore, in such case it is even more important to optimize the process parameters for high accuracy and efficiency and less of surface finish.

One of the most important is Pulse-on time (Ton). The discharge energy increases with Ton, and then the MRR is also enhanced with Ton. On the contrary, in MMCs it is discovered that the long Ton results in high heat generation, deep craters, rough surfaces, and thickening of the recast layer. As for the sparks energy, the small Ton also generates low spark energy and limits cutting speed, thereby making the state of machining shake.

The pulse-off time (Toff) is also significant and establishes the time between firing events. The longer Toff allows for more rapid quenching of the spark gap to avoid a short during the MMC fabrication with abrasive reinforcement particles. If the Toff is set too long, APS is reduced and productivity is degraded. The challenge is to select a best Toff that will give us sparking and debris removal for reliability, and lose as little speed as we can.

The spark energy and the material removal rate are determined by the discharge current. Increasing the current increases MRR but too much of it causes severe thermal damage (micro-cracking, warping) to MMC components. Since MMC reinforcements are resistant to thermal erosion, soft matrix is preferentially eroded by high current, which is led to roughing of the cross sections.

9ire stress The stress of the wire is very contributory to the straight cuts and to the dimensiona1 accuracy. Low tension can cause the wire to vibrate, leading to wider kerfs and worse surface quality, and overly high tension can increase the risk of wire breakage, especially in hard or thick MMC sections. The wire feed rate is also controlled to ensure the wire feed rate per unit time is a constant feed value.

The machining stability is largely influenced by the dielectric fluid pressure and flushing mode. Efficient flushing also contributes to the removal of swarf and cooling of the area of the workpiece, which is important especially in MMCs with obstructive clogging of the spark gap by reinforcement particles. Underflushing tends to cause arch instability, wire breakage and poor surface finish.

Some of the control features, such as servo voltage and wire offset, also have performance impacts. For better reproducibility and to prevent short circuits, the spark gap distance is adjusted via the servo-voltage. Wire offset will also compensate for kerf width variations which are produced in heterogeneities other than the MMC material.

Optimization of the best values of these parameters for MMCs involves the author adjusting the ranges of these parameters systematically by methodologies such as Taguchi DOE and RSM. This kind of strategies are really helpful in identifying statistically significant factors, and in setting parameter values that accomplish the best compromise among speed, accuracy and integrity of surface results.

In conclusion, the influence of process parameters on WEDM performance is profound and for MMCs, it needs to be very cautiously adjusted so as to strike a trade-off between the productivity and high surface finish for critical applications. Understanding these influences allow the WEDM conditions to be optimized for the various composite compositions and provide maximum benefit for the reliability and cost.

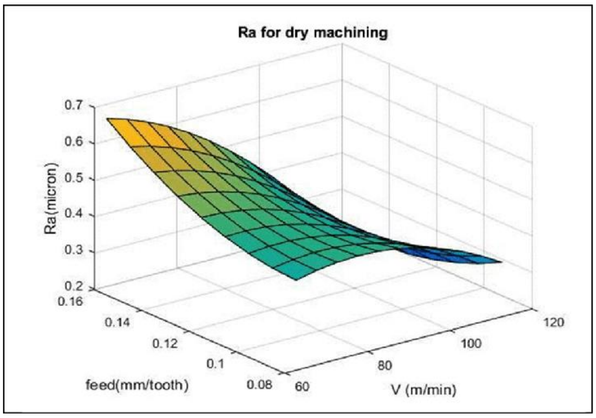

Figure 4: Impact Of Process Parameters On Machining Performance

V. EXPERIMENTAL INVESTIGATIONS AND OPTIMIZATION TECHNIQUES

It is crucial to have an estimate for the behaviour for the MMCs machining (Wire EDM) theoretically and experimentally with the optimal machining machining parameters. Due to its complicated microstructure, MMCs consisting of ductile matrix and hard abrasive reinforcement, the evaluation of the parameters can help to interpret the experimental results that are very difficult to explain by the theoretical models. These modelling are used to relate the WEDM input parameters with the output responses (such as material removal rate (MRR), surface roughness (Ra), kerf width and surface integrity).

The experimental parameters for investigation are chosen by way of a critical review of experimental work. Typical parameters such as power-on time (Ton), power-off time (Toff), flushing amount, the tension of the wire, the feed rate of the wire, and the pressure of the dielectric washing liquid, are employed. In the case of MMCs, the properties (and state) of the reinforcement, the size and volume fraction of reinforcement are also factors influencing the machining characteristics. For example, it may be necessary to decrease Ton and increase flushing pressure to prevent the retention of debris and the non-uniform approach due to high SiC fraction of MMCs.

Researchers have generally employed Design of Experiments (DOE) techniques to analyze these interactions in a systematic manner. One such method Taguchi's method has gained a lot of popularity due to its ability to reduce number of experimentations and also be able to point out important factor. Orthogonal arrays are used to arrange the experiments and Signal-to-Noise (S/N) ratios are used to assess robustness of parameter settings. Namely by the "larger-the-better" S/N criteria, when maximization of MRR is desired and by the "smaller-the-better" when minimization of the surface roughness is required, it is reasonable.

After collecting the data ANOVA is used to ascertain the particle size and the significance of each parameter. That allows for examining which factors are most governing in machining results. For example, it has been reported that, in MRR, Ton is the major factor compared to Toff and wire tension which are key influential on the surface finish by studies done. It enables scientists to focus on the most important factors for further optimizations.

The Response Surface Methodology (RSM), as an optimization approach to construct mathematical models that are able to approximate the relationship between the process variables and response variables, is also used. Given these models, one can make response surface and contour plots to demonstrate the way in which two or more factors interact graphically. Such models are useful to infer the performance, to identify the optimal conditions without conducting extensive experimentation.

Apart from statistical analysis, recent experimental designs applied multi-objective optimization methods (such as GRA, GA, etc.). These methods permit simultaneous optimization of conflicting target functions like maximum MRR and minimum Ra and Kerf width. This is crucial for MMCs as a good surface finish is frequently compromised for productivity.

Some experimental studies were also performed on the optimisation of tool materials and the effect of dielectric. For instance, zinc-coated brass wires can lead to less frequent breaking of the wire in high reinforcement MMCs, or a powder suspension dielectric can lead to better surface finish due to spar k spacing stabilization and reduced thermal damage.

Overall the good experimental investigations and good optimization reveals the performance improvements of the WEDM process on MMCs. Scientists and engineers can, based on the systematic analyses of the parameter effects, develop cutting strategies to provide for high precision and low surface roughness at an economic machining process, to enable the use of these composites in high-end engineering applications.

VI. INFLUENCE OF WEDM ON SURFACE INTEGRITY AND MICROSTRUCTURE OF MMCS

The surface integrity is a significant characteristic for the machining process since it directly affects functional performance, fatigue life and reliability of a component. In WEDM with MMCs the surface quality is controlled not exclusively by the phenomena of electric discharge, but also by the heterogeneity of the workpiece. Although very selective cuts are possible, the high energy spark erosion composition is restricted in its use as the heat is locally focused to about 8000-12000°C, with significant physical and metallurgical impacts on the workpiece's surface being effected.

One of the most important effects on the surface integrity is the formed recast layer, that is the solidified thin film of molten (melt from the spark discharge) that forms at the high cooling rate multiplier on the workpiece. In MMCs, such a layer may enwrap unmolten or partly molten reinforcing particles and give a rough surface. But continued thick recast layer is not desirable, as it is likely that the latter contains micro-cracks and voids acting as stress raisers which lower the fatigue strength of the part.

Another common microstructural change is the existence of a heatAffeareà zone (HAZ) beneath the machined surface. The HAZ is the area in which the base metal microstructure has been altered by the heat of welding, although not melted. In MMCs the matrix is metallic, and can undergo grain growth phase transformation or softening, while the ceramic reinforcement cannot generally be influenced by the effect due to its high melting experience. The mismatch in thermal response of matrix and reinforcement, can lead to local thermal stresses, and therefore to a greater likelihood of micro-crack nucleation.

The micro cracks are such another surface defect observed after WEDM. These might be due to rapid thermal cycling when its surface is heated and then rapidly cooled down to room temperature in a μs-time-scale for each discharge. Thermal mismatch between ductile matrix and hard reinforcement also contributes to crack initiation. In service, these cracks may propagate under loading leading to premature failure.

In addition to these, surface roughness (Ra) is one of the indicators for the surface integrity. The more deep and large the pit the rougher the formed surface, and the greater the discharge energy the rougher the surface. In MMCs the process of selective wear would work to degrade softer matrix, but also protruding reinforcement particles by increasing surface roughness. Post machining processes like polishing or laser finishing is an option to comply with demanding surface quality requirements.

From a microstructural perspective, WEDM can also cause the release of residual stresses in MMCs workpieces. These internal stresses are generated due to the temperature difference across the phases of the material, and can be either tensile or compressive. While residual compressive stresses can sometimes be beneficial in fatigue life, tensile stresses are typically damaging as they accelerate the growth of the crack.

These effects may be mitigated by careful selection of the process parameters. Reducing the pulse-on time, the use of the optimal flushing, and the adoption of the powder-mixed dielectric conditions can reduce the recast layer thickness and the HAZ width, and enhance the surface roughness. In addition, by containing a wire material having hardness higher than the above in which wear resistance is higher, a cutting treatment can be stabilized so that surface property can be raised.

In short, understanding and management of surface integrity in the WEDM of MMC are the cornerstones for obtaining the conformed dimensional and functional parts. Thermal effect management, debris removal, and spark stability control allow the production of high-quality surfaces with low micro-structural changes, an issue of significance in the long-term service of MMC components in extreme environments.

VII. WEDM OF MMCS IN COMPARISON WITH OTHER MMC MACHINING OPERATIONS

For the machining of MMCs, comparing WEDM with other processes is very much important to understand the advantages, limitations and applications. MMC is extremely difficult for traditional machinability by its soft ductile matrix and hard abrasive additives. So the performance factors such as MRR, surface finish, dimensional accuracy, tool wear, cost effectiveness and usability for complex shapes can only be compared.

Conventional means of manufacturing — turning, milling, drilling — all involve contact between the cutting tool and the workpiece. Although these are acceptable for softer metals, an increase in tool wear due to the abrasiveness in the ceramic reinforcement (i.e., SiC or Al_2O_3) is greatly exacerbated in harder materials, such as MMCs. This means frequent changing of tool and more stops and high cost of operation. Furthermore, it is difficult to achieve high accuracy due to deflections of the cutting tool, the vibration, and the difference in the material removal with the matrix state and the reinforcement state. This can damage the surface roughness with the reinforcement particles obviously protruding and microcracking when it is observed under higher magnification.

An instance of above radical thermal removal method may be the conventional EDM (diesinking EDM) though even this is not as suitable for machining cavities, dies, moulds. Without a continuous wire feed as in WEDM, it is less productive to cut complex shapes or profile sections of large planar sections even though it has an ability to machine MMCs.

Laser beam machining (LBM) and abrasive waterjet machining (AWJM) are options too. In LBM, a high energy laser is employed to heat and evaporate a substance. It has big cutting speed and causes extensive heat-affected zone (HAZ), therefore threat to thermal deformation of MMCs. In contrast, AWJM cuts by mechanical erosive action of high velocity abrasive laden water. Though AWJM does not induce ther- mal damages as does WEDM, its multi-dimensional sensitivities of a workpiece are not as high as those of WEDM, and its cutting speeds may be slower for thicker MMC sec- tions.

IX. APPLICATIONS AND PROSPECTS WEDM FOR MMCS ENVIRONMENTALLY FRIENDLY TURNING OF MMCS BY WEDM

Wire Electrical Discharge Machining (WEDM, is identified as a headline precision manufacturing technique for Metal Matrix Composites (MMCs) industry to fully exploit the high strength, wear resistance and thermal stability of the (MMCs). Applications of WEDM in machining of MMC are extensive too aerospace, automotive, defence, bio-medical instruments and electronics. In the aerospace sector, WEDM is used to produce turbine blade, structural bracket and heat resistant part where close tolerance and low residual stresses are the requirement. It finds its application in automotiveengineering especially in engine parts, brake parts and in the suspension, mar if lightweight construction MMC‘s, for example Al-SiC-Composites, are used with high load-carrying-conditions. In biomedical industry, there are MMCs based orthopedic implants, surgical instruments and dental equipment that WEDM can also be used to handle, since the process does not convicted mechanical stress in producing complex geometries and biocompatible surface finishes.

It also can be expected that the WEDM technology for MMCs would be more and more promising in the near future with the development trend of miniaturization, of complex geometry manufacturing and of integration on Industry 4.0. The micro-WEDM, capable of wire-cut machining using wires 30 microm thick or Letlimeter, will also be even more demanded, with the growth of those complicated micro-features in the microelectronics, aerospace instrumentation, and medical-devices fieLIs, for such a gap is 20 11lICro thiCk. On the other side, the development of intelligent control algorithms and parameter optimization techniques will also allow WEDM machine tools to change operating conditions based on real-time information collected in the machining zone, providing a constant quality level despite variations in the MMC microstructure. Although tool wear, surface quality and machining efficiency could be greatly improved by several numbers of hybrid WEDM systems, including ultrasonic-assisted, laser pre-treated and cryogenic-treated ones.

Sustainability On the sustainability front, WEDM's inherent advantages -- minimal material wastage, minimal cutting force, and high accuracy -- inherently brand it as instrumental to conservation of the environment vis-a-vis more conventional machining ....technologies that directly depend on tool consumption, and therefore, result in higher scrap generation." But, even now, there are sustainability issues such as the dielectric fluid of WEDM which should also be managed to prevent from environmental contamination. Future studies could also include sustainable dielectric alternatives and dielectric recycling systems, together with dry -WEDM processes which completely free the process from use of fluid. Furthermore, there are advances in energy performance i.e. optimal pulse generating systems and regenerative braking in wire drives of WEDM processes, which can decrease the carbon footprint.

Another sustainability relevant issue is the potential recycling of MMC. WEDM has the advantage of generating accurate cutting with little damage to material and is suitable for recycling and reusing components, which meets the requirement of the principle of circular economy. Also, there is no need to machine away excess stock material on near-net-shape parts, saving material.

The further development of WEDM in digital manufacturing systems will be an important trend to follow. By integrating the developed modules on digital twins, a simulation of the MMC-machining will become possible under different conditions, which results in virtual optimization before the actual processing. This reduces the trial-and-error cycles, speeds up lead times and saves time and money during the production process. When applied with real-time IoT monitoring, WEDM operations can be more predictable, efficient, and environmentally friendly.

Summing up the WEDM will be the up and coming role for machining the MMCs for the industries to search for a perfect manufacturing solution with precision, performance and sustainability in a better way. In addition, with the technology improvements, green machining, and the technology integration into smart manufacturer system, WEDM will be still the most advanced technology for MMC in the following tens of years.

X. CONCLUSION

A study on process of Wire Electrical Discharge Machining (WEDM) of Metal Matrix Composites (MMCs) is an obligatory cesspool of advanced materials & precision manufacturing. They exhibit – steroidlike properties compared to classic ceramics, and are by far the most significant of all man-made materials for aerospace, automotive, biomedical, and defense uses. The former, however, are very hard substances and difficult and time consuming to cut in a traditional fashion. Compared with other finishing processes (grinding and EDM grinding), EDM is a non-contact thermoelectric erosive process, stably and controllably and is well-suited for small, complex, and thin wall shapes with no mechanical stress to the work piece.

From the above on material properties, processing parameters and process performance, it is evident that the WEDM has higher potential for machining different MMCs with respect to other machining processes. Since pulse on-time, pulse off-time, peak current, wire tension and dielectric flushing can be fine-tuned, productivity and surface integrity can be optimized to the particular engineering needs. However, as the microstructure of the MMC is complex and the distribution of the reinforcement within the MMC is typically not homogeneous, the optimization of the process parameters need to be performed carefully in order not to generate problems such as wire breaking, micro-cracking, or nonuniform material removal.

Analysis also reveals that technological advancements; like AI based adaptive control, micro-WEDM and hybrid WEDM processes, aided in the progress of WEDM. These are particularly relevant in high-tech environments where precision and dependability are essential. The digital manufacturing boost “Integration of WEDM with digital manufacturing

Productive advances like digital twins and IoT-based monitoring could enhance predictability, reduce downtime and contribute to a more sustainable production ecosystem."

Sustainable becomes a crucial point for the development of WEDM in MMC machining. Although process concept reduces material waste and tool tooling wear of traditional machining but various problems related to dielectric fluid treatment and energy consumption are reported. These issues can be addressed by the application of "green" dielectrics, recycling systems and energy-efficient machine designs to bring WEDM in compliance with global sustainability objectives and circular economy principles. Furthermore, near-net-size production of components from MMCs by WEDM reduces raw material utilization, as well as facilitates recycling and reconditioning of high-quality parts.

From the results, WEDM is both not only a complementary process, but also a basic process for advanced MMC incremental forming part. It machines to high levels of quality and efficiency with a diverse range of types of reinforcement, matrix alloys and applications. Future developments regarding the thermal model and the discharge energy control, as well as the surface treatment, will enhance the potential application in next generations MMCs for demanding applications.

To sum up, Wire EDM is a mixture of precision, versatility, and innovation in bunch machines. With the requirement of the advanced lightweight, high strength materials from the industries; in future the WEDM will become a potential emerging technology. Taking advantage of the most advanced technology and pushing process parameters to the limit, and adding sustainability to the equation, WEDM is able to not only meet the needs of the ever-evolving modern day manufacturing-demand-ready components capable of operating in the harshest of conditions-but also live up to the calls for efficiency, performance and environmental conscience for many decades ahead.

XI. REFERENCES

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