International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
Volume 46, Issue: Special Issue of December 2017
An Indexed, Referred and Peer Reviewed Journal with ISSN (Online): 2319-6564
www.ijesonline.com

An Overview of Current Research Trends in Wire Electrical Discharge Machining

Deepak Kumar Sethy [1*], Jitendra Padhi [2]

[1*] Assistant Professor, Department of Mechanical Engineering, Nalanda Institute of Technology, Bhubaneswar, Odisha, India

Assistant Professor, Department of Mechanical Engineering, Nalanda Institute of Technology, Bhubaneswar, Odisha, India

*Corresponding author e-mail: deepakkumar@thenalanda.com

ABSTRACT : Advanced engineering materials like super alloys, composites, and ceramics are created as a result of advances in material science. These materials are tough and challenging to work with, and they frequently provide challenges to smooth machining using conventional machining techniques including turning, milling, drilling, and grinding. Such sophisticated materials are successfully machined using non-traditional machining processes.

The stock is cut using a non-traditional machining technique called wire electrical discharge machining (WEDM), which involves burning a gap through the material with heat generated by an electrical spark between the workpiece and a wire that is submerged in a dielectric fluid that serves as a coolant and flushes away the scrap. WEDM satisfies the demands of the machining and tooling sectors. Without the use of expensive grinding or cutting tools, WEDM is a vital machining technology for generating intricate cutouts through difficult-to-machine metals.

A review of the WEDM research that has been published shows that the focus of current study is on the more recent features of wire EDM in the areas of analysis and optimization. To forecast material removal rate and surface finish while milling AISID2 tool steel under various machining conditions, mathematical models have been developed. In order to forecast and optimise the surface roughness and cutting velocity of the WEDM process in the machining of SUS 304 stainless steel materials, a neural network model and simulated annealing algorithm have been developed. Artificial neural networks and response surface methods have been used to estimate the cutting speed and surface roughness of the EDM process (ANNs).**Keywords:** Advanced material, WEDM, Optimization, Mathematical modelling.

I. INTRODUCTION

A type of EDM that falls under the heading of non-traditional machining processes is wire-electrical discharge machining. In the manufacture of dies, this is frequently utilised. Via a sequence of discrete discharges between the wire electrode and the work piece while a dielectric fluid is present, electrically conductive materials are cut utilising the electro-thermal mechanism. In the area where discharge takes place, a very high temperature results in melting and removal of the work surface. The debris from the machining zone is flashed by the dielectric fluid. This technique is commonly used to create components with complex forms and features. Nevertheless, WEDM uses a continuous travelling wire electrode with a very small corner radius that is formed of thin brass, tungsten, or copper wire with a diameter ranging from 0.05 to 0.03 mm.

The tension in the wire is created using a mechanical tensioning mechanism. There is less stress between the work piece and the wire because there is no direct contact between them [1]. Independent of their hardness, shape, or toughness, electrically conductive materials can be successfully sliced using the WEDM technique [2-4]. Moreover, the WEDM technique can produce high-precision parts.

II. WEDM

This section provides the basic principle of WEDM process as well as other material removal methods.

A. Basic Principle of WEDM Process

The mechanism of material removal in WEDM is similar to conventional machining process in which erosion effect produced by the series of electrical sparks produced between the work piece & the wire electrode surrounded by stream of dielectric fluid continuously flowing in the machining Zone [5]. A temperature range of 8000°C–12,000°C exist between cathode and anode in the form of thermal energy after applying voltage pulses between the work–piece and the wire electrode during WEDM process. When the pulsating DC power supply occurring between 20,000 and 30,000 Hz is turned off, the plasma channels breaks down.

As a result of breaking of plasma channel a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten

Heat-treated steels and materials with high strength and temperature resistance (HSTR).

particles from the machining zone in the form of microscopic debris [6].

There are two main types of EDM: ram or die–sinking EDM, and travelling–wire, wire–cut or simply wire–EDM. The fundamental principle, in the either kind is similar. A power supply initiates a voltage difference between the electrode and the electrically conductive grounded work piece. As the tool approaches the work piece, the electric field strength grows in the gap until the dielectric medium separating the tool and the work piece breaks down. A plasma channel is created after the dielectric ionises, compressing the surrounding dielectric. The temperature of plasma may reach as high as 40,000K and pressure of 3K. bars. As both electrons and ions bombarded on the surface of work piece, heating of the work piece takes place such that a portion of surface is melted. However, the plasma pressure prevents vaporization.

When discharge takes place, the plasma channel collapses and a vapour bubble occurs which causes the superheated molten material of work piece surface to explode into the dielectric. The ejected material is flushed away; whereas portions of the molten material resolidify onto work piece surface which is called as the recast layer [7]. Fig. 1. shows details of WEDM cutting gap [8].

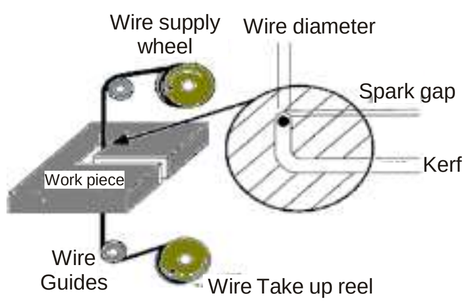

Fig.1. Details of WEDM cutting gap.

WEDM reduces the need of elaborate pre–shaped electrodes that are commonly necessary in EDM to perform both the roughing and finishing operations. In WEDM, a thin wire is used which is continuously feeding through the work piece by a microprocessor. Microprocessor helps the parts to be machined into complex shapes with exceptional high accuracy. In WEDM a plasma channel between the cathode and anode exist due to supplied electrical energy [9], and finally converted into thermal energy [10] after reaching a temperature in the range of 8,000° –12,000°C [11] or as high as 20,000°C. As a result of which heating & melting on the surface of both the poles takes place. As soon as the pulsating DC power supply occurring between 20,000 to 30,000 Hz [12] is turned off, the plasma channel breaks down and there is sudden reduction in the temperature flush the molten particles from the machining zone in the form of microscopic debris. The microprocessor also maintains constantly the gap between the wire and the work piece varies from 0.025 to 0.05 mm [4].

The typical cutting rates in case of WEDM are 300 mm^2/min. for a 50 mm thick D2 tool steel and 750 mm^2/ min. for 150 mm thick aluminium [12], and surface finish is as fine as 0.04–0.25μRa. WEDM makes use of deionised water instead of hydrocarbon oil as dielectric fluid flowing within the sparking zone. Though the deionised water is not suitable for conventional EDM as it causes rapid electrode wear, but it is ideal for WEDM because of its low viscosity and fast cooling rate [13].

B. Hybrid Machining Process

To get the benefit of both WEDM and other machining methods, hybrid machining processes (HMPs) are used. WEDG is one such hybrid machining process, which is used for producing the micro– parts that have a wide application in an electronic industry. The WEDG makes use of a single wire guide to confine the wire tension within the discharge area to reduce the wire vibration. Therefore using this technique can produce a rod of diameter as small as 5μm [14] with high accuracy, good repeatability and satisfactory straightness [15].

In order to improve the performance measures such as SF and CR of the WEDM process, ultrasonic vibration assisted WEDM process is applied. Ultrasonic assisted WEDM is used to improve surface quality, CR and to minimise the residual stress on the machined surface [16]. In addition to this, wire electrochemical turning (WECT) process enhances the productivity of the process and improves the surface quality together with roundness error [17]. The wire electrochemical grinding (WECG) process replaces the wire electrical discharge used in WEDG with an electrochemical solution to produce high quality of surface finished part for a wide range of machining condition [18].

III. WEDM APPLICATIONS

This section discusses the capability of the WEDM process in the machining of the different materials used mainly in tooling applications.

A. Modern Tooling Applications

The feasibility of making use of cylindrical WEDM for dressing a metal bonded diamond wheel used for precision form grinding of ceramics has been studied [19]. It has been found that the WEDM process is capable of producing precise and intricate profiles with small corner radii with high wear rate on grinding wheel during the first grinding pass. Over–protruding diamond grains, which don't bond strongly to wheel after the WEDM process results in high initial wheel wear rate [20].

B. Advance Ceramic Materials

Advance ceramic materials are machined with the help of an alternative method which is nothing but WEDM [1].

Dauw *et al*. [21] explained that the material removal rate and surface roughness are not only influenced by the cutting parameters it depends on the material of the part.

Matsuo and Oshima [22] studied the influence of conductive carbide content (named NbC) and TiC, on the cutting rate and surface roughness of zirconia ceramics (ZrO_2) during WEDM.

Takayuki Tani [23] proposed arbitrary shaped machining method of insulating ceramics (Si_3N_4) by WEDM. During WEDM of thick workpiece of Si_3N_4 insulating ceramics, It was observed that frequent wire breakage occurs. Therefore, a new assisting electrode material was used to avoid frequent wire breakage. Warping phenomenon was also observed towards the end of product during machining of thin sheets due to thermal residual stress. The amount of warp can be reduced by considering the machining path.

C. Modern Composite Materials

WEDM is considered as a real tool as compared to different material removal processes in machining of different modern composite materials. Manna and Bhattacharyya [24] performed experiments using a typical four–axes Electronica Supercut–734 CNC–wire cut EDM machine on aluminium–reinforced silicon carbide metal matrix composite Al/SiC MMC. Open gap voltage and pulse on period are the most major machining parameters, for controlling the metal removal rate. The cutting speed affected significantly by open gap voltage.

Wire tension and wire feed rate were the most significant machining parameters, for the surface roughness. Wire tension and spark gap voltage setting were the most significant for monitoring spark gap [25]. Yan *et al*. [26] surveyed the different machining processes performed on the metal matrix composite and experimented with the machining of Al_2O_3/6061 Al composite by using rotary EDM coupled with a disc–like electrode. It was found that the process parameters have little impact on SR but have a contrary effect on CR. Patil and Brahmankar investigated the performance of Al/SiCp composites with wire electro–discharge machining [28]. It was found that the process parameters such as pulse on–time, off–time, ignition pulse current, wire speed, wire tension, and flushing pressure on cutting speed and surface finish affect the performance of WEDM of Al/SiCp composite. A comparative study on unreinforced alloy revealed the effect of reinforcement.Cuttin speed for unreinforced alloy was found higher compared to composites whereas surface finish in composites was found superior than the unreinforced alloy. Wire breakage is one of the limitations on the cutting speed of composite. Jangra *et al*. [29] proposed a Graph theoretic approach (GTA) to evaluate the machinability of WC composite. It was found that among the five factors, machine tool has the highest index value. Therefore, machine tool factor is the most influencing factor that affects the machinability of WC composite. Fig. 2. shows research studies conducted in both EDM and WEDM on metal matrix composite [27].

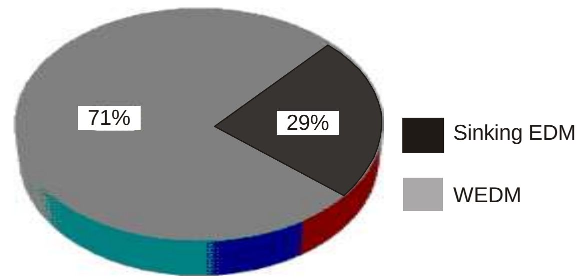

Fig. 2. Research studies conducted in WEDM on MMCs.

IV. MAJOR AREAS OF WEDM RESEARCH

The various WEDM research have planned into two major areas namely WEDM process optimization together with WEDM process monitoring and control.

A. WEDM Process Optimization

Nowadays, the most effective machining approach is determined by finding the different factors affecting the WEDM process and tries to find the different ways of obtaining the optimum machining condition and performance. This section provides a study on the several machining strategies including the design of the process parameters and modelling of the WEDM process. For obtaining the optimal machining performance, it is necessary to set the various machining parameters in WEDM process. This section shows selected analytical and statistical methods used to study the influence of the various parameters on the typical WEDM performance measures such as MRR, SF, wire crater size and CR.

(a) Factors Affecting the Performance Measures

As the wire electric discharge machining is a complex machining process, so it is controlled by large number of process parameters like pulse duration, discharge current intensity, and discharge frequency etc. A little variation in these parameters can affect the performance measures of WEDM such as MRR, SR CR etc [30]. Kumar *et al*. [31] studied and found that the pulse on time parameter has direct effect on MRR during machining of pure titanium. In addition to this when pulse off time is increased the MRR decreases. Tosun *et al*. [32] has found that increasing the pulse duration, open circuit voltage, and wire speed increases the crater diameter and crater depth. Prashar *et al*. [33] has shown that MRR of EDMed work piece depends on gap voltage, pulse on time and pulse of time while machining of SS304L using statistical regression analysis.

(i) Effect of process parameters on cutting rate. Various problem–solving quality tools have been used to investigate the important factors and their inter–relationship with the other factors in obtaining an optimum WEDM cutting rate.

Garg *et al*. [35] have studied that the cutting rate is directly affected by the pulse–on time, pulse off time, peak current, spark gap set voltage as well as the wire feed and wire tension in machining titanium alloy 6–2–4–2.

(ii) Effect of Process Parameters on MRR (Material Removal Rate). Material removal rate is one of the most important machining performance measures which are affected by various parameters under consideration in WEDM.

Rao *et al*. [36] investigated the effects of on time Ton), pulse off time Toff), peak current, flushing pressure of dielectric fluid, wire feed rate, wire tension, spark gap voltage (SV), and servo feed (SF) setting in machining of Aluminium BIS–24345 alloy using CNC Wire cut process.

They have shown that IP is the most significant and Ton, Toff, SV and SF are significant using ANOVA. In addition to this they have found that an optimum MRR can be obtained by using Signal–to–Noise (S/N) ratio. Mohammadi *et al*. [37] evaluated the effects of machining parameters on MRR, expressing the mathematical relationship between machining parameters and MRR and presented the optimal machining conditions using ANOVA with S/N ratio.

(iii) Effect of Process Parameters on SR. After detailed review of the research papers, it was found that a number of research work published which studied the influence of machining parameters on the WEDMed surface. Tosun *et. al*. [38] investigated the effect of cutting parameters such as pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the surface roughness of WEDMed surface. The result had shown that an increase in pulse duration, wire speed and open circuit voltage increases the surface roughness, whereas increasing the dielectric pressure decreases the surface roughness. Pasam *et al*. [39] determined the optimal parameters for surface finish under varying conditions using the Taguchi design process in WEDM of Ti_6Al_4V alloy. Balasubramanian *et al.* [40] studied the optimum process parameters to obtain lower SR using Grey rational analysis in machining of Inconel 718 by WEDM. The experimental result s confirms that the method used i.e. Grey relational analysis effectively improves the performance measures of WEDM process.

Routara *et al.* [41] had shown that the performance characteristics of the WEDM process like MRR and SR are improved together by using Grey relational analysis in machining of AISI D3 tool steel. Mahapatra and Patnaik [42] studied effects of various parameters on SF on performance measures of WEDM process in machining of D2 tool steel using Genetic Algorithm (GA). It was found that SF largely depends on the process parameters like discharge current, pulse duration, pulse frequency, wire speed, wire tension and flow rate of die lectric fluid.

(b) WEDM Process Modelling. Modelling of WEDM process is applied to relate effectively the various process parameters to the different performance measures using mathematical techniques, Artificial Neural Network (ANN) etc. Ramakrishnan and Karunamoorthy [43] developed the modeling techniques using ANN and analysis of variance (ANOVA) to predict performance measures such as material removal rate (MRR) and surface roughness (SR) by varying pulse on time, delay time, wire feed speed, and ignition current. Han *et al.* [44] developed a simulation model which replicates the discharge phenomena of WEDM accurately in the same manner as in WEDM. An adaptive control is used that automatically generates an optimal machining condition for précised WEDM. Raju *et al*. [45] investigated the process parameters to achieve better machining accuracy in terms of kerf width and cutting speed in case of WEDM of HT Brass alloy using mathematical modeling and optimization techniques. It was found that peak current, pulse on time; pulse off time; wire feed and offset are the significant parameters to evaluate the kerf width and cutting speed. Datta and Mahapatra [46] established a mathematical model to highlight parametric influence on the three selected process responses: MRR, SR and width of cut. They found the Response surface method is efficient for the prediction of process responses for the different combination of parameter setting.

B. WEDM Process Monitoring and Control

This section investigates the advanced monitoring and control system such as fuzzy logic, wire breakage and self–turning adaptive control system used in WEDM process. To monitor and evaluate the gap condition, a servo feed control system with proportional controllers have been used traditionally during wire electric discharge machining [1]. Lee. Liao [47] proposed a control system to improve the efficiency of machining a workpiece with varying thickness in WEDM process. They used a gain self–turning fuzzy control algorithm to achieve stable performance. They show that the cutting speed can be obviously improved by the proposed control strategy. Liao and Woo [48] designed a fuzzy controller integrated with an online pulse monitoring system isolating the discharging noise as well as discriminating the ignition delay time of each pulse. Chin *et al.* [49] developed a control strategy based on fuzzy logic to improve the machining accuracy at corner part for WEDM.

V. DISCUSSION AND FUTURE RESEARCH DIRECTIONS

A. Optimising the Process Variables

As per the research work available, it is clear that even a single parameter change will change the process in a complex way [50]. So optimization of the wire electrical discharge machining process repeatedly found to be a difficult work. To get the actual trends of the process variation, it is required to understand the impact of various factors on the WEDM process as already.

To optimize the process parameters using various statistical and analytical methods is required to get an optimal performance measures. It is difficult to relate input parameters with an output performance measures to derive an optimal. Fig. 3. Shows the classification of main research domain of wire electrical discharge machining [1].

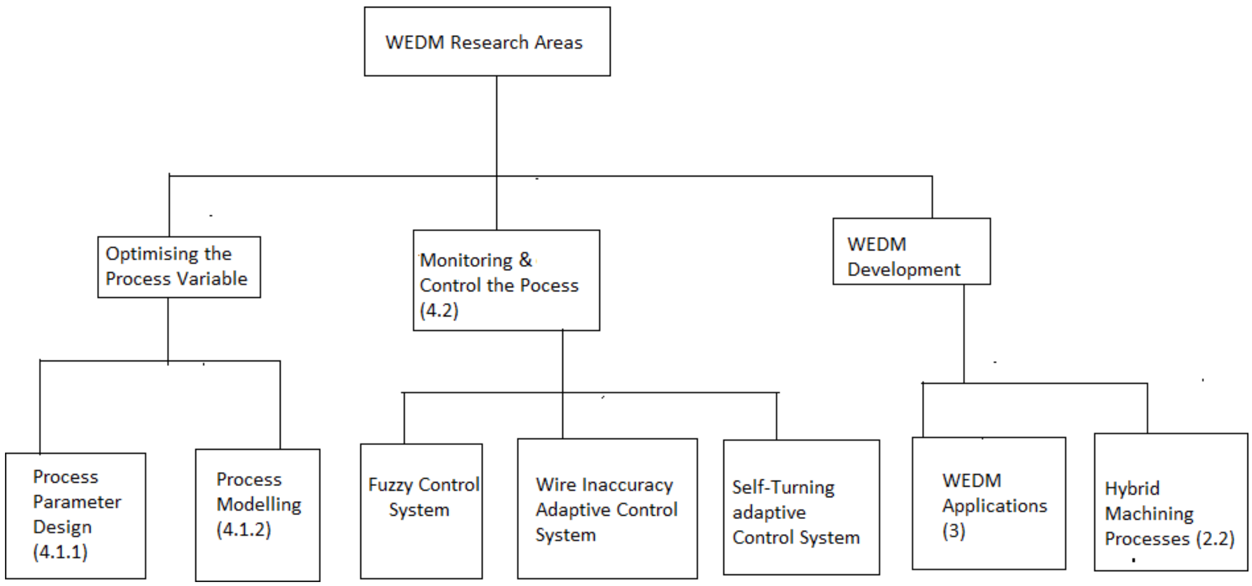

Fig. 3. Classification of major WEDM research domain.

In addition to this, modelling of the process is another effective solution of the tedious problem concerning the process parameters to the performance measures. As above mentioned in section (*b*), many models have developed to investigate the effect of the process parameters on WEDM performance measures and to get the optimal condition from the infinite number of combination. However, the WEDM process requires the application of deterministic and stochastic techniques as the process is itself of complex and random nature [51]. So, optimisation of the WEDM will be always the key research domain to relate many process parameters with the performance measures.

B. Monitoring and Control the Process.

Monitoring and control of WEDM process is one of the important contribution for the last few years. In order to obtain the optimal machining conditions, it requires control algorithm based on explicit mathematical and statistical models. The fuzzy control logic is having capability to consider several process variables affecting the process and make changes to machining condition without applying detained mathematical model. as discussed in section (*B*). As the risk of wire breakage and wire bending limited the efficiency and accuracy of WEDM process, an adaptive control system has developed to identify online the abnormal behaviour in wire breakage. The abnormal behaviour in wire breakage directly reduces the machining speed results in adverse effect in overall productivity of the WEDM process.

After the detailed review of literature it was found a lot of the works have been done in the area of monitoring and control and few work has been done in the area of optimization of process variables whereas the work in the area of WEDM developments have been done more than the area of optimizing process variables and less than the area of monitoring and control the process.

C. WEDM Developments

The rapid growth in the development of harder and difficult–to–machine materials has taken place for the last two decades. As traditional edged machining methods are not suitable for machining such materials because it results in poor degree of accuracy and surface finish [54].

The modern machining methods are not limited by hardness, brittleness and toughness of the materials. Moreover it can produce any intricate shape on harder and difficult–to–machine materials. It has been commonly used in the automotive, tool and die, aerospace, medical, dental and jewellery industries [52]. As described in the section III, the wire electrical machining of advance ceramic like SKD–11 and ZrO_2 and modern composite with growing trend has also been experimented by several authors.

The researchers have classified the WEDM machine into various physical characteristics which distinguishes the different features influencing the performance measures, auxiliary facilities and machining capacity as shown in Fig. 4. There are number of hybrid machining process (HMP) developed by researchers used to manufacture micro sized and complex shaped products [1]. Among the various HMP process, one of the most précised arrangement is the WEDG process used for producing complex shaped and small products which can't be manufactured by conventional grinding process. The WEDG is used extensively in micro–electronic circuitry manufacturing and will continue to get intense research attention in the coming decades.

The performance measure of the WEDM process is also depends upon the skill of operator. The requirement of the skilled operator is been fulfilled through the application of the CNC controlled machining strategy. The CNC–wire EDM is not only to fulfil the requirement of skilled operator but also to prevent the wire breakage and employed for automating the self threading systems. In addition to this an environmental friendly and a high capacity dielectric regeneration system to maintain the quality of the dielectric flowing in machining zone [43]. The innovative mechanism can be applied to manufacture complicated surfaces through WEDM process [54].

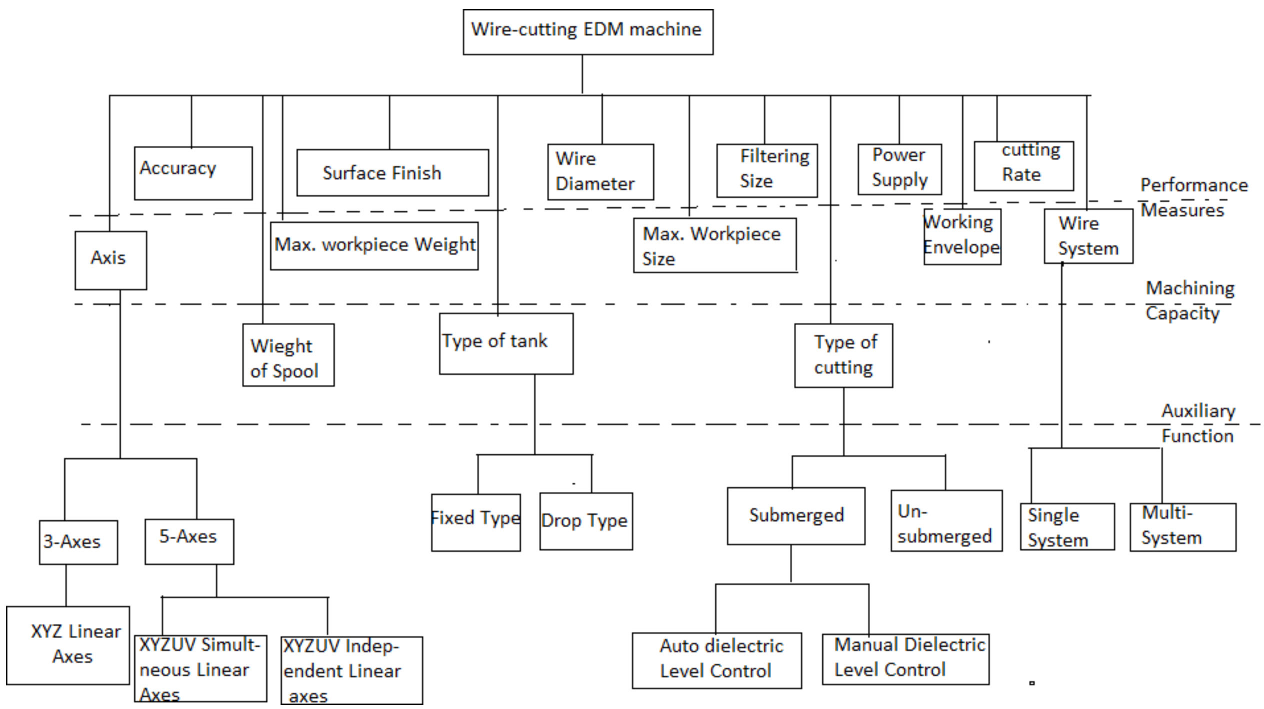

Fig. 4. Classification of WEDM machine.

VI. SUMMARY

A non-traditional machining technique called WEDM is employed to meet the demands of various metal cutting sectors. It is utilised while creating intricate two- and three-dimensional designs employing electrically conductive workpieces and longitudinally moving wire electrodes. This WEDM technique has been widely used where tight dimensional tolerances and high profile accuracy are required. It is independent of the workpiece's hardness value. As compared to other non-traditional machining methods, this process' primary drawback is its comparatively slow machining speed (such as Laser beam machining, Electrochemical etc.). The usage of the WEDM method in the upcoming decades will be made more difficult by the recent advancements in materials.So, therefore it is very necessary to make continuous improvement in the current WEDM process to increase their productivity and efficiency.

The primary goal of the WEDM method is to achieve the ideal parameters without sacrificing its performance metrics. To stop wire breaks during the WEDM process, the adaptive control approach must be used. Mathematical models must also be established in addition to the new monitoring and control algorithms based on expert systems or intelligent systems in order to lessen the error brought on by vibrational or static deflection of wire. In the current modern production environment, it is imperative that the WEDM process be sufficiently enhanced in order to keep up with the highly competitive and cost-effective machining technology.

REFERENCES

[1] Ho, K.H. and Newman, S.T., State of art in wire electrical discharge machining (WEDM), *Int. J. Mach. Tools Manuf.* **44:** 1247–1259(2004).

[2] Kansal, H.K., Sehijpal, S., and Pradeep K., Technology and research developments in powder mixed electric discharge machining (PMEDM). *J. Mater. Process. Technol* **184:** 32–41(2007).

[3] Abu Zeid, O.A., On the effect of electro–discharge machining parameters on the fatigue life of AISI D6 tool steel. *J Mater Process Technol* **68**(1): 27–32(1997).

[4] Ramasawmy, H, Blunt. Effect of EDM process parameters on 3D surface topography. *J Mater Process Technol* **148:** 155–164(2004).

[5] Puri A.B., and Bhattacharyya B., An analysis and optimization of the geometrical inaccuracy due to wire lag phenomenon in WEDM, Int. J. Mach. Tools Manuf. **43**(2): 151–159(2003).

[6] Bojorquez B, Marloth RT, Es–Said O.S. Formation of a crater in the work piece on an electrical discharge machine. *Eng Fail Anal,* **9:** 93–97(2002).

[7] Bhosale S.M., Nandedkar V.M. and Patil S.B., Surface modifications in Wire–EDM of Advance materials: A Review, *Int. J. Manuf. Science and Technology* **3**(2): Dec., pp. 171–183(2009).

[8] Mahapatra, S.S. and Amar Patnaik, Parametric optimisation of wire electrical discharge machining (WEDM) process using Taguchi method, J. of the Braz. Soc. Of Mech. Sci. & Eng., Vol. XXVIII No. **4:** 422–429 (2009).

[9] Shobert E.I., What happens in EDM, in: E.C. Jameson (Ed.), Electrical Discharge Machining: Tooling, Methods and Applications, Society of Manufacturing Engineers, Dearbern, Michigan, pp. 3–4(1983).

[10] Tsai, H.C., Yan B.H., and Huang F.Y., EDM performance of Cr/ Cu–based composite electrodes, Int. *J. Mach. Tools Manuf.* **43**(3): 245–252(2003).

[11] Boothroyd, G., and Winston, A.K., Non–conventional machining processes, Fundamentals of Machining, Marcel Dekker, Inc, pp. 4911989.

[12] McGeough, J.A., Electro discharge machining, Advanced Methods of Machining, Chapman & Hall, London, pp. 130(1988).

[13] Huntress E.A., Electrical discharge machining, *Am. Machinist* **122**(8): 83–98(1978).

[14] Masuzawa T., and Tonshoff H.K., Three–dimensional micromachining by machining tools, Ann. CIRP **46**(2): 621–628(1997).

[15] Masuzawa T., Fujino M., Kobayashi K., Suzuski T. and Kinoshita N., Wire electro–discharge grinding for micro–machining, Ann. CIRP **34**(1): 431–434(1985).

[16] Guo Z.N., Lee T.C., Yue T.M., Lau W.S., A study of ultrasonic–aided wire electrical discharge machining, *J. Mater. Process. Technol.* **63**(1–3): 823–828(1997).

[17] Taha Ali–El–Taweel, Gouda S.A., Performance analysis of wire electrochemical turning process–RSM approach, *Int. J. Adv. Manuf Technol,* **53:** 181–190(2011).

[18] Masuzawa, T., Kuo C.L., Fujino, M., A combined electrical machining process for micro nozzle fabrication, Ann. CIRP **43**(1): 189–192(1994).

[19] Rhoney B.K., Shih, A.J., Scattergood, R.O., J.L., Akemon D.J. Grant, M.B. Grant, Wire electrical discharge machining of metal bond diamond wheels for ceramic grinding, Inter. *J. Mach. Tools Manuf.* **42**(12): 1355–1362(2002).

[20] Rhoney, B.K., Shih, A.J., Scattergood, R.O., R. Ott, S.B. McSpadden, Wear mechanism of metal bond diamond wheels trued by wire electrical discharge machining, Wear 252(7–8) 644–653(2002).

[21] Dauw D.F., Brown C.A., J.P. Van Griethuysen, J.F.L.M. Albert, Surface topography investigations by fractal analysis of spark–eroded, electrically conductive ceramics, Ann. CIRP **39**(1): 161–165(1990).

[22] Matsuo T., and Oshima E., Investigation on the optimum carbide content and machining condition for wire EDM of zirconia ceramics, *Ann. CIRP* **41**(1): 231–234(1992).

[23] Takayuki Tani, Yasushi Fukuzawa, Naotake Mohri, Nagao Saito, Masaaki Okada, Machining phenomena in WEDM of insulating ceramics, *J. of Material Processing Technology* 149, pp. 124–128(2004).

[24] Manna, A., Bhattacharyya, B., Taguchi and Gauss elimination method: A dual response approach for parametric optimization of CNC wire cut EDM of PRAISiCMMC, *Int. J. Manuf Technol,* **28:** 67–75(2006).

[25] Garg R., PhD Thesis, Mechanical Engineering, NIT Kurukshetra, Haryana, (2010).

[26] Yan, B.H., and Wang, C.C., W.D. Liu, and Huang F.Y., Machining characteristics of Al2O3/6061Al composite using rotary EDM with a dislike electrode, *Inter. J. Adv. Manuf. Technol.* **16**(5): 322–333(2000).

[27] Garg R. K., Singh K.K., Sachdeva A., Sharma V.S., Ojha K., Singh S., Review of work in sinking EDM and WEDM on metal matrix composite materials, *Int. J. Adv. Manuf Technol*, (50) pp. 611–624(2010).

[28] Patil N.G., Brahmankar P.K. some investigations into wire electro–discharge machining performance of Al/SiCp composites. Int *J Machin Mater* **1**(4): 412–431(2006).

[29] Jangra K., Grover S., Felix T.S. Chan, Aggarwal A., Digraph and method to evaluate the machinability of tungsten carbidecomposite with wire EDM, *Int J Manuf Technol,* **56:** 959– 974(2011).

[30] Alekseyev, G.A., M.V. Korenblum, Analysis of the Conditionsfor the High Efficiency Wire Cut EDM, Proceedings of the Ninth International Symposium for Electro–Machining (ISEM–9), Nagoya, Japan, (1989).

[31] Kumar A., Kumar V., Kumar J., Effect of machining parameters on MRR during CNC WEDM of Pure Titanium, *Proc. Of the Fifth International Conference on Advances in Mechanical Engineering*, June 06–08, pp. 541–545(2011).

[32] Tosun N., Cogun, C., Pihtili, H., the effect of cutting parameters on Wire crater sizes in Wire EDM, Int *J Manuf Technol* (21) pp. 857–865(2003).

[33] Prashar V., Rehman A., Bhagoria J.L, Puri Y.M, Statistical and Regression analysis of material removal rate for wire cut Electro Discharge Machining of SS304L using design of experiments, *Int. J of Engineering Science and Technology,* Vol. **2**(5): 1021–1028(2010).

[34] Saha P., Saha P., Pal S. K, Parametric optimization in WEDM of WC–Co composite by Neuro–Genetic Technique, *Proceedings of the World Congress on Engineering*, Vol. III, July 6–8, 2011, London, UK (2011).

[35] Garg M. P., Jain A., Bhushan G., Investigation of the effect of process parameters in wire EDM of High Temperature Titanium Alloy 6–2–4–2, *Proceedings Of the Fifth International Conference on Advances in Mechanical Engineering*, June 06–08, pp. 626–630(2011).

[36] Rao P.S., Ramji K., Satyanarayana B., Prediction of material removal rate for Aluminium BIS–24345 Alloy in wire–cut EDM, *Int J Manuf Science and Tech* Vol. **2**(12): 7729–7739(2010).

[37] Mohammadi A., Fadaie A. Tehranie, Emanian, E., D. Karimi, Statistical analysis of wire electrical Discharge turning on material removal rate, *J Materials Processing Technology* **205**, pp. 283–289(2008).

[38] Tosun N., Cogun, C., A. Inan, The effect of cutting parameters on workpiece surface roughness in wire EDM, *Machining Sci. Technol*. **7**(2): 209–219(2003).

[39] Pasam V. K., Batulla S. B., Madar Valli P., Swapna M., Optimizing surface finish in WEDM using the Taguchi Parameter Design Method, *J. of Braz. Soc. Of Mech. Sci. & Tech.* April–June, Vol. XXXII, No.2 pp. 107–113(2010).

[40] Balasubramanian S., Ganapathy S., Grey Relational Analysis to determine optimum process parameters for wire electrical discharge machining (WEDM), *IJEST*, Vol. **3** No.1 Jan ISSN: 0975–5462(2011).

[41] Routara B.C., Nanda B.K., Patra D.R., Parametric optimization of CNC wire cut EDM using Grey Relational Analysis, *Proceedings of the International Conference on Mechanical Engineering, Dhaka, Bangladesh* pp. 1–6 (2009).

[42] Mahapatra S.S., and Patnaik A., Optimization of wire electrical discharge machining (WEDM) process parameters using Genetic Algorithm, *Indian J of Engineering & Material Science*, Vol. **13:** December, pp. 494–502(2006).

[43] Ramakrishnan R., Karunamoorthy L., Modeling and multi–response optimization of Inconel718 on machining of CNC WEDM process, *J. of mat. Processing Technology* **207:** pp.343–349(2008).

[44] F. Han, M. Kunieda, T. Sendai, Y. Imai, High precision simulation of WEDM using parametric programming, *Ann. CIRP* **51**(1): 165–168(2002).

[45] Raju, M.V.J, Satyanarayana B., Ramji K., Subramanian R.V.S, Mathematical modeling and optimization of kerf width of wire electrical discharge machining (WEDM) of HT Brass Alloy, *Proc. Of the Fifth International Conference on Advances in Mechanical Engineering*, June 06–08,, pp. 641–646(2011).

[46] Datta S., and Mahapatra S.S., Modeling, Simulation and parametric optimization of wire EDM process using response surface methodology coupled with Grey–Taguchi Technique, *Int J of Engineering Science and Technology*, Vol. **2(**5): 162–183(2010).

[47] Lee W.M., and Y.S. Liao, Adaptive control of the WEDM process using a self–turning fuzzy logic algorithm with grey prediction, *Int J Adv Manuf Technol* **34:** pp. 527–537(2007).

[48] Liao, Y.S., Woo, J.C., Design of a fuzzy control system for the adaptive control of WEDM process, Inter. J. Mach. Tools Manuf. **40**(15): 2293–2307(2000).

[49] Chin–Teng Lin, I–Fang Chung, Shih–Yu Huang, Improvement of machining accuracy by fuzzy logic at corner parts for wire–EDM, Fuzzy sets and Systems 122. pp. 499–511(2001).

[50] Scott, D., and Boyina, S., K.P. Rajurkar, Analysis and optimization of parameter combination in wire electrical discharge machining, *Int. J. Prod. Res*. **29**(11): 2189–2207(1991).

[51] Williams, R.E., Rajurkar, K.P., Study of wire electrical discharge machined surface characteristics, *J. Mater. Process. Technol*. **28**(1–2) 127–138(1991).

[52] Stovicek, D.R., The state–of–the–art EDM Science, in: Tooling and Production, Nelson Publishing Inc., Ohio, US, **59**(2): May, pp. 42(1993).

[53] Levy, G.N., Environmentally friendly and high–capacity dielectric regeneration for wire EDM, *Ann. CIRP* **42**(1): 227–230(1993).

[54] Sahai N., M.E. Thesis, Mechanical Engineering, Thapar University, Patiala, Punjab (2009).