Hybridization of Electrical Discharge Machining Process

Mohd. Yunus Khan, P. Sudhakar Rao

Abstract*: This paper discusses the recent developments in the field of Electrical Discharge Machining (EDM) hybrid process. Spark machining is a universally recognised unconventional process, excluding the restriction of having low machining efficiency. To overcome this, various investigations have been made on designing of electrode, types of dielectric medium, variations in input parameters etc. Although material expulsion rate have been found to improve, nonetheless it cannot encounter the requirements of modern industries and the quality of surface is inferior. To increase further the utility of EDM, its hybridization with other process have to be carried out. A hybrid process can reduce the machining time while maintaining better surface and material expulsion rate. In hybrid process, the mechanism of two processes is applied concurrently or consecutively. Although, the performance of combined process is better as compared to the individual processes but hybridization increases the process complexity.

***Keywords* : Electrical Discharge Machining (EDM), Hybrid Machining, Material removal rate (MRR)).**

I. INTRODUCTION

Electrical Discharge Machining (EDM) process is popular from more than seven decades [1]. Other names for this type of machining are spark machining and spark eroding. Process of EDM has gained popularity worldwide and substituted conventional machining operations. In this method, stock is eroded from the sample because of chain of speedily repeating current discharges amidst twin electrodes, which are parted employing dielectric fluid and made prone to a potential difference [2]. One of the electrodes is tool while the other is work-piece. The shape of the material removed is controlled to develop an object with required geometry and surface finish. This process is employed to machine hard metals like titanium and pre-hardened steel and materials which can't be easily machined using traditional process. Spark machining is engaged for machining electrically conductive materials. This type of machining is commonly used for producing moulds and dies and mass production of ordinary items. Large number of the conventional processes (like drilling, grinding and milling) has been unsuccessful in machining geometrically complicated contour and size. Such materials are conveniently machined by using this process. It can as well manufacture accomplished parts including cutting tools and products with intricate shapes.

Revised Manuscript Received on October 15, 2019

***** Correspondence Author

Mohd. Yunus Khan, PhD Scholar, Department of Mechanical Engineering, National Institute of Technical Teacher's Training and Research (NITTTR), Chandigarh, India.

Email: khan_yunus123@rediffmail.com

P. Sudhakar Rao, Assistant Professor, Department of Mechanical Engineering, National Institute of Technical Teacher's Training and Research (NITTTR), Chandigarh, India. Email: psrao.iitr@gmail.com

II. SIGNIFICANCE OF THE PROCESS

Ability of Electrical discharge machining process to function solitarily for hours or days enhance its utility. Through this process, it becomes easy to work on hard and difficult to machine materials [3]. Components having complicated, specific and inconsistent dimensions and complex inner configuration can be easily manufactured by using this machining process. Tiny aperture in hardened steel of carbide can be produced by specially designed Cu-W electrodes, employing a micro machining attachment [4]. Composites and ceramics, which are otherwise hard to work, conceivably machined using EDM method. Spark machining can be used for producing gear and internal threads cutting [5]. It finds extensive applications in manufacturing of mould and die [6]. It has made its presence felt in aerospace, automotive, telecommunication and biotechnology industries [7]. Its applications can also be found in the electronics, healthcare, optics, sports, jewellery making and toys manufacturing [8].

III. MERITS OF ELECTRICAL DISCHARGE MACHINING PROCESS

EDM offers multiple merits over conventional machining methods.

1) Material removal in spark erosion process is predominantly dependent upon thermal characteristics of the workpiece material instead of mechanical properties [9].
2) Forces developed during machining operation are negligible.
3) Difficult-to-machine materials can easily be machined [10].
4) Complicated cutting profile, pointed and briery angles and internal junctions can be easily developed.
5) Components produced are free from mechanical stress, rotation of work sample or tool is not required and such machines offer greater autonomy [11].
6) Delicate and slender sections like webs and fins can be produced conveniently with no distortion of the components.
7) Machining of hardened material could be carried out without any distortion attributable to heat treatment.
8) No burrs are produced on the surface after machining [12].

IV. LIMITATIONS OF EDM PROCESS

EDM operation has following limitations

1) The workpiece and tool used must be electrically conductive.
2) Sometimes the wear rate of tool is greater due to which more than one tool may be needed to complete the required operation.
3) Optimal settings of the machining operation to a great extent are affected by the tool-workpiece combination. Machine manufacturers only provide settings for certain tool-workpiece combinations. Hence, great skills are needed to develop own technology. [4]
4) Metal erosion rate in as case of spark machining is relatively low. Also, Overall machining operation is slower in comparison to conventional process [8].

V. HYBRID MACHINING PROCESS

A number of processes are being used in industries for manufacturing required part. These processes includes CNC machining, additive manufacturing, transformative processes etc. Every process has some inherent constraints which puts limit to its use. Hence, owing to technological restrictions, manufacturing of parts in terms of shape, dimensions, surface quality becomes infeasible [13, 14]. Hybrid machining is basically amalgamation of different machining processes for machining component with a superior machining efficiency. This process utilizes the group or mutually profiting results of at least two individual processes. This moreover evades or possibly reduces some adverse effects produced by the individual processes [15]. With the advancement in the area of hybrid machining, the productivity has significantly increased. By utilizing hybrid machining processes, it is possible to achieve machining of the advanced materials, improvement in machining precision and development of complicated designs which was earlier difficult or impossible to machine.

A hybrid process can be broadly classified as:

a) Assisted hybrid machining process In such process, the material expulsion occurs by the primary source and the secondary source only assists it. Examples are LASER-assisted turning, vibration-assisted EDM, Ultrasonic assisted electro chemical machining (ECM) etc.
b) Combined hybrid machining process In this process, several material removal mechanisms simultaneously work on the workpiece and takes part in material expulsion. Examples are mechano-electrochemical machining, electrochemical discharge machining, electro discharge grinding and abrasive-EDM processes, abrasive-water jet milling etc.
c) Controlled application of process mechanism In this process, different processes are combined on the same machine. Such an arrangement also reduces the process chain. E.g. grind hardening, stretch bending combined with single point increment forming [16].

VI. OBJECTIVE OF PRESENT STUDY

A number of researches have been conducted on evolving various design of electrode, different types of dielectric medium, various machining parameters, relative movement tool-workpiece, mixing of powder and so on. The basic aim of these investigations was to cater advanced materials, enhancing material expulsion rate, reducing electrode wear, achieving better surface quality, increasing machining efficiency etc. To increase further the utility of EDM, its hybridization with other process have been carried out. A small number of studies are available on hybridization of EDM processes. The scrutiny of such researches is presented here.

VII. STUDIES ON HYBRIDIZATION OF EDM PROCESS

Lin et al. (2000) [17] experimentally explored machining attributes of Ti-6Al-4V utilizing combined EDM and ultrasonic machining (USM) processes. In this investigation, variables including as dielectric variety, abrasive size and concentration, peak current and pulse duration were varied to study their influence on material removal rate (MRR), electrode wear rate (EWR), relative electrode wear rate (REWR), surface roughness (SR) and thickness of the recast layer. It was observed that hybrid machining can build the MRR and lessen the extent of the recast layer. Further, hybrid process can significantly diminish abnormal discharge accordingly discharge efficiency can be improved.

Zhang et al. (2006) [18] investigated a technique known as ultrasonic assisted EDM, in which EDM in gas and ultrasonic vibrations were combined together. They conducted experiments on AISI 1045 using copper electrode. They found that MRR increased with increment in open voltage, pulse duration, amplitude of ultrasonic actuation and current. SR was found to increase with increment in open voltage, pulse duration and discharge current.

Ji et al. (2010) [19] introduced combined EDM and mechanical grinding process for machining ceramic. It was found that MRR increased, REWR decreased and SR increased from finish machining to rough machining. Under similar conditions, lower SR was achieved with +ve tool polarity and greater MRR and lesser REWR were achieved with -ve tool polarity. It was also noticed that stock from the electrode can get be transferred to the work sample and a combined reaction can happens during machining with +ve tool polarity, which forms the thickness of modified layer on the surface after machining surface. On the other hand, there were no obvious response occurring during machining with -ve tool polarity.

Kim et al. (2010) [20] proposed a hybrid process for micro-machining combining nano-second pulsed Laser and micro-EDM. Experimentation showed that considerable reduction in machining time of EDM drilling and milling can be achieved by quick LASER pre-machining before micro EDM. They also fabricated few complex three dimensional micro structures using combined manufacturing process.

Lin et al. (2012) [21] built up a hybrid process combining abrasive jet machining (AJM) and EDM. Abrasives at high speed were impinged on the machined surface to evacuate the recast layer developed during by EDM operation and to enhance material expulsion rate and lessen SR. The test results showed that hybrid process has a better machining efficiency and surface quality.

Nguyen et al. (2012) [22] examined simultaneous micro-EDM and micro-ECM (SEDCM) so as to accomplish improved surface finish and machining efficiency. Material expulsion process in micro-EDM using low-resistivity de-ionized water was studied. Three key elements of this hybrid machining, namely low-resistivity de-ionized water, low feed rate and short voltage pulses were identified. SEDCM improved the surface finish and decreased SR. The electrochemical reaction adds to the disintegration of the influenced material inside the white layer and the heat affected regions.

Zeng et al. (2012) [23] conducted micro-EDM and micro-EDM combined milling for three dimensional micro-structure. They conducted these processes in succession on the same machine tool having unchanged electrode but changed dielectric fluid. The results showed that the machining efficiency and shape accuracy vastly improved in comparison to that obtained with micro-ECM milling alone. The surface finish and mechanical property of the work sample also improved.

Ji et al. (2013) [24] investigated hybrid machining combining end electric discharge (ED) milling and mechanical grinding. Method was applied to SiC ceramic with varying input parameters to analyse their impact on the surface finish and composition of the part after machining. The results showed fine surface finish can be obtained using +ve tool polarity, short pulse on-time and low peak current. It was also seen that during the hybrid process, the material was largely expelled by end ED milling at rough machining, whereas it is removed by mechanical grinding at finish machining.

Lin et al. (2013) [25] investigated the machining attributes of ultrasonic vibration assisted EDM process employing gas as dielectric fluid. For experimentation, SKD 61 steel was used as the work sample and Cu as electrode. It was observed that the machining polarity and peak current were important factors influencing MRR and SR. They observed that suggested hybrid machining fit to the demands of advanced manufacturing applications.

Kozaka et al. (2016) [26] developed Abrasive Electrical Discharge Grinding technique and investigated the performance characteristics of hard materials. Machining processes included traditional grinding, hybrid process and traditional grinding with in-situ EDM grinding wheel dressing. Application of EDM during grinding permitted an increment in machining efficiency and lessens requirement of wheel dressing during machining. Hybrid process resulted in poor surface finish as compared to traditional grinding.

Li et al. (2016) [27] investigated hybrid process combining EDM and end milling (EDM-end milling) and presented a mathematical model of the same. Further, they contrasted simulated and test outcomes for validation of the model. Tungsten carbide end mill was used for machining STD 11 alloy steel with varying electric pulses. It was observed that EDM-end milling was a viable technique for machining hard material. Remarkable improvement in the machining efficiency was observed contrasted to EDM process alone. SR and tool wear were also observed to improve using hybrid process. Notwithstanding, the surface finish diminished with high energy pulse.

Lin et al. (2016) [28] explored the machining attributes of gas medium EDM in combination with AJM and ultrasonic vibration. This technique was used to inspect the machining attributes of SKD 61 steel. It was seen that higher MRR was obtained with hybrid process. Further, MRR gained by O_2 dielectric medium has the greatest response while lowest EWR and finest SR were obtained using Ar. The ultrasonic vibration integrated hybrid process resulted in decrease of recast layer thickness. It was concluded that advance machining efficiency and surface finish can be obtained with hybrid machining.

Shen et al. (2016) [29] conducted EDM milling on AISI stainless steel 304 using a combination of arc machining and EDM as hybrid process with a high-speed air dielectric medium. Similar experiments were carried out using dry hybrid machining, dry arc machining and dry EDM. Higher MRR while lower REWR and SR were obtained in dry hybrid machining. It was observed that dry hybrid process is a proficient rough machining technique for removing materials.

Lin et al. (2018) [30] examined the machining attributes of gas medium EDM combined with AJM. Influences of input variables on output variables for SKD 61 tool steel were contemplated. It was observed that variables influencing MRR were machining polarity, peak current and pulse duration. Peak current was the most important variable with regards to the EWR. Peak current, pulse duration and gas pressure were significant with relation to SR. It was concluded that with this hybrid process better machining efficiency can be obtained.

VIII. SUMMARY

The summary of above researches is tabulated with investigations and conclusions in Table I. It can be referred for a quick insight of investigations studied in this paper.

Table I Overview of studies on EDM hybrid machining

S.No.	Ref. No.	Authors (Year)	Workpiece material, tool material and dielectric fluid	Investigations	Conclusions
1.	17	Lin et al. (2000)	**Workpiece material:** Ti-6Al-4V **Tool material:** Electrolytic Cu **Dielectric fluid:** Kerosene, distilled water	Performance of EDM with USM on MRR, EWR, REWR, SR and thickness of the recast layer.	➢ Combined EDM and USM processes build the MRR and lessen the thickness of the recast layer. ➢ Hybrid machining significantly diminished abnormal discharge accordingly discharge efficiency can be improved.
2.	18	Zhang et al. (2006)	**Workpiece material:** AISI 1045 **Tool material:** Cu **Dielectric fluid:** Air	Performance of ultrasonic assisted EDM (in gas).	➢ MRR increased with increment in open voltage, pulse duration, amplitude of ultrasonic actuation and current. ➢ SR increased with increment in open voltage, pulse duration and discharge current.
3.	19	Ji et al. (2010)	**Workpiece material:** SiC ceramic **Tool material:** Resin-bonded abrasive **Machining fluid:** Water based emulsion	Surface integrity of SiC ceramic machined using combination of Electrical discharge milling and mechanical grinding.	➢ MRR increased, REWR decreased and SR increased from finishing to roughing. ➢ Under similar conditions, lessen SR was achieved with +ve tool polarity and greater MRR and lower REWR were achieved with -ve tool polarity.
4.	20	Kim et al. (2010)	**Workpiece material:** Stainless steel (AISI 304) **Tool material:** WC **Dielectric fluid:** De-ionized water	Effect of utilizing combined nanosecond pulsed Laser and micro-EDM processes	➢ Considerable reduction in machining time was observed in EDM drilling and milling by quick LASER pre-machining before micro EDM. ➢ Complex three dimensional micro- structures were fabricated using combined process.
5.	21	Lin et al. (2012)	**Workpiece material:** SKD 61 steel **Tool material:** Electrolytic Cu **Dielectric fluid:** Air (compressed and Dehumidified)	Performance of hybrid AJM and EDM process.	➢ Hybrid machining has improved MRR, better machining efficiency and surface quality.
6.	22	Nguyen et al. (2012)	**Workpiece material:** Stainless steel (SUS304) **Tool material:** Tungsten **Dielectric fluid:** De-ionized water	Performance of concurrent micro-EDM and micro-ECM.	➢ Simultaneous micro-EDM and micro-ECM improved finish and machining efficiency while SR reduced.
7.	23	Zeng et al. (2012)	**Workpiece material:** Metallic micro-structure **Tool material:** Tungsten **Dielectric fluid:** EDM oil and ECM electrotyte	Performance of combined micro-EDM and micro-ECM milling for three dimensional micro-structure.	➢ Machining efficiency and shape accuracy vastly improved in comparison to that obtained with micro-ECM milling alone. ➢ Surface quality of the work sample also improved.
8.	24	Ji et al. (2013)	**Workpiece material:** SiC ceramic **Tool material:** Cu electrodes and cast iron bonded diamond abrasive sticks in the circumference **Machining fluid:** Water based emulsion (8% mass emulsified oil and 92% mass distilled water)	Evaluation of surface quality using combined end electric discharge (ED) milling and mechanical grinding	➢ Fine surface finish was obtained using +ve tool polarity, small on-time and low peak current. ➢ During hybrid process, the material was largely expelled by end ED milling at rough machining. While it is mostly expelled grinding at finish mode.

Retrieval Number: A9477109119/2019©BEIESP
DOI: 10.35940/ijeat.A9477.109119

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

9.	25	Lin et al. (2013)	**Workpiece material:** SKD 61 steel **Tool material:** Electrolytic Cu **Dielectric fluid:** Compressed air	Machining attributes of ultrasonic vibration assisted EDM process in gas media.	➢ Machining polarity and peak current were important variables influencing MRR and SR.
10.	26	Kozak et al. (2016)	**Workpiece material:** PCD, WC Duralcan and Ti-6Al-4V **Tool material:** Diamond grinding wheels **Dielectric fluid:** IONOGRIND (from OelHeld)	Machining of hard materials by using Abrasive Electrical Discharge Grinding.	➢ Application of EDM during grinding permitted an increment in machining efficiency and lessens requirement of grinding wheel dressing during machining. ➢ Hybrid process results in poor surface finish as compared to traditional grinding.
11.	27	Li et al. (2016)	**Workpiece material:** STD 11 alloy steel **Tool material:** Tungsten carbide **Dielectric fluid:** EDM oil	Performance of the hybrid machining combining EDM and end milling (EDM-end milling) processes.	➢ EDM-end milling was found to be a viable technique for machining hard materials. ➢ Boost in the machining efficiency, SR and tool wear was observed contrasted to EDM alone.
12.	28	Lin et al. (2016)	**Workpiece material:** SKD 61 **Tool material:** Electrolytic Cu **Dielectric fluid:** Air, oxygen and argon	Performance of EDM with combination of USV and AJM.	➢ Hybrid machining resulted in higher MRR. ➢ MRR gained by O_2 dielectric medium has the greatest response while lowest EWR and finest SR were obtained using Ar as a dielectric media. ➢ The ultrasonic vibration decreased the thickness of recast layer. ➢ With hybrid process, better machining affectability and surface quality were obtained.
13.	29	Shen et al. (2016)	**Workpiece material:** AISI 304 stainless steel **Tool material:** Graphite **Dielectric fluid:** Air	Performance of dry hybrid process of EDM and arc machining.	➢ Higher MRR while lower REWR and SR were obtained in dry hybrid machining. ➢ Dry hybrid machining found to be a proficient rough machining technique.
14.	30	Lin et al. (2018)	**Workpiece material:** SKD 61 tool steel **Tool material:** Electrolytic Cu **Dielectric fluid:** Air (compressed and dehumidified)	Effect of process variables of hybrid machining combining EDM and AJM on response variables.	➢ Peak current was the chief variable with regards to the EWR. ➢ Peak current, pulse duration and gas pressure were the main parameters with relation SR. ➢ Better machining efficiency was observed with hybrid machining.

IX. ANALYSIS AND DISCUSSION

A close look on the available literature shows that non-conventional machining operations have some merits and limitations. These limitations keep them away from being flexible. To surpass these limitations, additional process is chosen to hybridize it. This not only minimizes the limitations but also maximum the advantages. Thus, it can be said that the objective of hybridization of process is to get merit of the both the processes. With the advancements in hybrization techniques, it is possible to machine the novel materials conveniently and complicated contours can be produced.

The hybridization of machining processes is starting from elementary research to industrial application. Hybrid processes are continuously in the process of further development. Investigators have utilized many such hybrid techniques that are generally complicated. Hybridization of spark machining process is carried out with an attachment on the standard EDM without modifying the basic system.

Combination of EDM and mechanical grinding process improves the performance such as material removal rate. The MRR in hybrid process have been observed to be higher than the conventional EDM or grinding alone. The ultrasonic-assisted EDM improves the performance including MRR and surface roughness. Abrasive Electrical Discharge Grinding technique has been developed for hard materials. Implementation of this technique, resulted in an increase in machining efficiency and lessens requirement of wheel dressing is required. However, poor surface finish is obtained.

Micro-machining combining nano-second pulsed Laser and micro-EDM resulted in significant reduction in machining time. Most of the investigations have been conducted in the area of ultrasonic assisted EDM and AJM-EDM combination. Comparatively lesser wok is available on Laser assisted EDM process. Cost, space requirement or non suitability for industrial environment may be the reason for restricted use of laser system in laser assisted EDM process.

In general, the process hybridisations can enhance MRR as for the improvement of machinability and thus, productivity can be improved.

X. CONCLUSIONS

Elementary introduction to EDM and its importance over conventional machining methods have been studied. Various applications of EDM along with its merits and limitations have also been discussed. One of the major disadvantages of spark machining is slower machining time. A hybrid process can reduce the machining time while maintaining better surface and material evacuation rate. Limited research has been done on EDM hybrid machining. In this paper, a review of studies carried out on EDM hybrid machining has been successfully made and presented in a systematic order to give insight into the progress made in this area. It can be concluded that hybridization of EDM is a better option achieving improvement in machining efficiency and reduction in machining time.

REFERENCES

1. Schumacher BM. After 60 years of EDM the discharge process remains still disputed. Journal of Materials Processing Technology. 2004;149:376-381
2. McGeough JA. Advanced methods of machining, London: Chapman and Hall Ltd.; 1988.
3. Dauw F, Coppenolle BV. On the evolution of EDM research. Part 2: from fundamental research to applied research. In: 11th International Symposium for Electro Machining (ISEM-XI), Lausanne, Switzerland, pp. 133-142; 1995.
4. Patel NK. Parametric optimization of process parameters for EDM of stainless steel 304: M.Tech. Dissertation, Department of Mechanical Engineering, National Institute of Technology, Rourkela; 2014.
5. Saindane TY, Patil HG. Electrical discharge machining-a state of art, International Journal of Innovative Science, Engineering and Technology. 2016;3(2): 262-266.
6. Singh SK, Jayswal SC. Modeling and optimization of EDM Process Parameters on Machining of Inconel 686 using RSM, International Journal of Applied Engineering Research. 2018;13(11):9335-9344.
7. Ali MY, Banu A. Electrical discharge machining (EDM): a review, International Journal of Engineering Materials and Manufacture.2016;1(1):3-10.
8. Dewangan SK. Multi-objective optimisation and analysis of EDM of AISI P20 tool steel, Doctoral Thesis, Department of Mechanical Engineering, National Institute of Technology, Rourkela; 2014.
9. Jagtap VL. A review of EDM Process for difficult to cut materials, International Research Journal of Multi-disciplinary Studies. 2016;2(1):1-6
10. Sato T, Mizutani T, Kawata K. Electro-discharge machine for micro-hole drilling, National Technical Reports. 1985; 31;725-733.
11. Descoeudres A. Characterization of electrical discharge machining plasmas: Centre de recherches en physique des plasmas (CRPP), Ecole Polytechnique Fédérale, Lausanne; 2006.
12. Singh BK, Yadav GS, Yadav A. Study on electric discharge machining and scope for new era, International Research Journal of Engineering and Technology. 2016;3(6):2214-2219.
13. Tawakoli T, Azarhoushang B. Influence of ultrasonic vibrations on dry grinding of soft steel. International Journal of Machine tools and Manufacture. 2009;48(14): 1585-1591.
14. Kolleck R, Vollmer R, Veit R. Investigation of a combined micro-forming and punching process for the realization of tight geometrical tolerances of conically formed hole patterns. CIRP Annals-Manufacturing Technology. 2011;60(2):331-334.
15. El-Hofy HAG. Advanced Machining Processes: Nontraditional and Hybrid Machining Processes. New York: McGraw Hill Professional; 2005.
16. Singh K, Maurya SK, Kumar S. A review of introduction to hybrid machining process, International Journal of Advanced Engineering and Technology. 2018;2(3): 22-26.
17. Lin YC, Yan B.H, Chang YS. Machining characteristics of titanium alloy (Ti-6Al-4V) using a combination process of EDM with USM, Journal of Materials Processing Technology. 2000;104(3):171-177.
18. Zhang QH, Du R, Zhang JH, Zhang QB. An investigation of ultrasonic electrical discharge machining in gas, International Journal of Machine Tools and Manufacture. 2006;46(12-13):1582-1588.
19. Ji RJ, Liu YH, Zhang YZ, Li H, Cheng XD. Machining performance and surface integrity of SiC ceramic machined using electrical discharge milling and the mechanical grinding compound process, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2010;224(10):1511-1518.
20. Kim S, Kim BH, Chung DK, Shin HS, Chu CN. Hybrid micromachining using a nanosecond pulsed laser and micro EDM, Journal of Micromechanics and Microengineering.2010;20(1):015037.
21. Lin YC, Chen YF, Wang AC, Sei WL. Machining performance on hybrid process of abrasive jet machining and electrical discharge machining, Transaction of Nonferrous Metals Society of China. 2012; 22:s775-s780.
22. Nguyen MD, Rahman M, Wong YS. Simultaneous micro-EDM and micro-ECM in low-resistivity deionized water, International Journal of Machine Tools and Manufacture. 2012;54-55:55-65.
23. Zeng Z, Wang Y, Wang Z, Shan D, He X. A study of micro-EDM and micro-ECM combined milling for 3D metallic micro-structures, Precision Engineering. 2012; 36(3): 500-509.
24. Ji R, Liu Y, Zhang Y, Cai B, Li X, Zheng C. Effect of machining parameters on surface integrity of silicon carbide ceramic using end electric discharge milling and mechanical grinding hybrid machining, Journal of Mechanical Science and Technology. 2013;27(1):177-183.
25. Lin YC, Chow HM, Tsui HP, Chen YF. Study on ultrasonic vibration in gas and optimization of a novel process of EDM, Advanced Materials Research. 2013; 675: 365-369.
26. Kozaka J, Maria ZS, Skrabalak G. Development of advanced Abrasive Electrical Discharge Grinding (AEDG) system for machining difficult-to-cut materials, Procedia CIRP. 2016;42:872-877.
27. Li CP, Kim MY, Islam M.M, Ko TJ. Mechanism analysis of hybrid machining process comprising EDM and end milling, Journal of Materials Processing Technology. 2016;237:309-391.
28. Lin YC, Hung JC, Chow HM, Wang AC, Chen JT. Machining characteristics of a hybrid process of EDM in gas combined with ultrasonic vibration and AJM, Proccedia CIRP. 2016;42:167-172.
29. Shen Y, Liu Y, Sun W. High-efficent dry hybrid machining of EDM and arc machining, Proceedia CIRP, 2016;42:149-154.
30. Lin YC, Hung JC, Lee HM, Wang AC, Fan SF. Machining performances of electrical discharge machining combined with abrasive jet machining, Proceedia CIRP. 2018;68:162-167.

AUTHORS PROFILE

Mohd. Yunus Khan is pursuing is Ph.D. (Mechanical Engineering) under QIP Scheme from NITTTR, Chandigarh. He is an Assistant Professor of Mechanical Engineering, University Polytechnic, Aligarh Muslim University, Aligarh.

Dr. P. Sudhakar Rao is working as an Assistant Professor in the Department of Mechanical Engineering, NITTTR, Chandigarh. He has done is Ph.D. (Mechanical Engineering) from IIT, Roorkee. His area is specialization is CAD, CAM, CIM and Non-Conventional Machining.