Analysis of breakdown property of the composite machining method of abrasive jet and electrical discharge

Xue Bai\textsuperscript{1,2}, Tingyi Yang\textsuperscript{1}, Rongguo Hou\textsuperscript{1}, Jianbing Meng\textsuperscript{1} and Xinran Mao\textsuperscript{1}

\textsuperscript{1}School of Mechanical Engineering, Shandong University of Technology, Zibo 255000, China
\textsuperscript{2}Corresponding author: lz8016@126.com

Abstract. To improve the machining quality and machining efficiency, the abrasive jet flow is used to replace the conventional electrical discharge dielectric medium, and then the composite machining method of abrasive jet and electrical discharge is proposed. The experimental setup and machining principle of the composite machining method is illustrated. The breakdown property is analysed using the Laplace's equation and its solution equation of the Gauss's law in the differential form in the spherical coordinates. The ability limitation of the dispersion phase to weaken the dielectric strength of the electrical discharge machining fluid and the water are calculated, respectively. The conductive abrasive, the air and the Al\textsubscript{2}O\textsubscript{3} non-conductive abrasive could weaken the dielectric strength of the electrical discharge machining fluid to 0.33 times, 0.83 times and 0.55 times, respectively. They could weaken the dielectric strength of the water to 0.33 times, 0.67 times and 0.69 times, respectively. The breakdown characteristics of different dielectric medium used in the composite machining method are analysed based on the calculating results. The water-air-Al\textsubscript{2}O\textsubscript{3} non-conductive abrasive is the working medium with the stable characteristic. The conductive abrasive-air-electrical discharge machining fluid is the working medium with the controllable characteristic.

1. Introduction

Electrical discharge machining (EDM) is also called electric spark machining. The electro erosion phenomenon between the electrode and the workpiece is used to remove the materials in this technology. In this technology, the thermal energy is used, and the electrode and the workpiece could not contact with each other. Meanwhile, no obvious cutting force acts on the workpiece. This non-conventional machining method is used widely in the field of Aeronautics and Astronautics, medical appliances, and mold manufacture, etc. There are great advantages of the EDM in machining the high hardness materials when compared with the conventional machining technology. However, its machining quality and machining efficiency still could not meet the engineering demand excellently.

The combined machining processes apply two or more effects including physical effect, chemical effect, and mechanical force to the machined workpiece. The shortcomings of each independent machining method could be overcome or weakened with the highlighting of their advantages. In order to improve the machining quality and machining efficiency of the EDM, researches are done on the combined EDM processes. The combined EDM processes apply spark erosion with chemical energy or mechanical force to the machined workpiece.

The electrical discharge grinding is a combined machining method which integrates the EDM and the conventional grinding. Yin et al. [1] fabricated micro rod electrodes by the electrical discharge grinding method. The experimental results showed that the machining efficiency was improved,
meanwhile, the error between machined diameter and target diameter was less than 2μm and the cylindrical error of micro electrode was also less than 2μm. Kozak et al. [2] developed an advanced abrasive electrical discharge grinding system for machining difficult to cut materials. The experimental results revealed that the combination of EDM method and the traditional grinding method could improve the machining efficiency effectively. Satyarthi and Pandey [3] proposed a mathematical model of the material removal rate in electric discharge grinding method based on the fundamental principles of material removal in EDM and conventional grinding processes to reveal the mechanism of material removal in electrical discharge grinding. The surfaces of the machined alumina ceramic samples were investigated by scanning electron microscopy. It was verified that the material removal process of the electric discharge grinding was a synthetic process of thermal effect and mechanical effect.

In order to improve the machining efficiency, the ultrasonic machining and the EDM is combined to present a new process called ultrasonic assisted EDM [4,5]. Lin et al. [6] machined SKD 61 steel by the hybrid process of EDM and ultrasonic vibration. Higher material removal rate, higher relative tool wear rate and lower machined surface roughness were found compared with the EDM process in gas. Goiogana et al. [7] did research on the influence of ultrasonic assisted EDM on the machined surface in the finishing operations. It was pointed out that the machined surface roughness and the homogeneity of the craters could be improved by the ultrasonic assisted EDM. Kurniawan et al. [8] fabricated the Carbon Fiber Reinforced Plastics (CFRP) composite by the ultrasonic assisted dry EDM (US-EDM). A higher burr removal rate was found when the pulse on time was less than 200μs.

The electrochemical discharge machining is another combined non-traditional machining method that integrated electrochemical machining and EDM [9]. This machining process is worldwide recognized due to the reason that it could be used to fabricate conductive materials, non-conductive ceramics, composite materials, alumina, glass and so on [10]. Kang et al. [11] successfully machined micro holes on ceramic coated superalloys by the electrochemical discharge machining method. The obtained current waveforms revealed that only the electrochemical discharge occurred during the machining of the coating layer; both the electrochemical discharge and the electrical discharge appeared when machining the superalloy substrate, however, the electrical discharge which occurred between the electrodes and the superalloy was the main factor causing material removal; compared with the traditional EDM method, the surface roughness of the hole sidewall decreased and the mean thickness of the recast layer decreased in the electrochemical discharge machining method. Zhang et al. [12] machined nickel-based superalloy workpieces using tube-electrode by the electrochemical discharge machining method. The flushing condition was enhanced through enlarging the inner hole diameter of the tool electrode, as a result, the machining efficiency and the machined surface quality were improved. Elhami and Razfar [13] did analytical and experimental study on the integration of ultrasonically vibrated tool into the micro electro-chemical discharge drilling. It was verified that this combined machining method could obtain higher machining efficiency and machining precision.

The combined machining method improves the machining characteristics by applying two or more energy forms integrately. Furthermore, the dielectric medium of the EDM is another important factor influencing the machining characteristics. The machining quality and machining efficiency could be improved by using suitable dielectric medium [14]. Through supplying deionized water at a controlled rate to the high-speed air pipe, Shen et al. [15] afforded a mist dielectric to the machining process and did study on the machining characteristics of the high-speed near dry EDM method. This novel machining method obtained higher material removal rate and lower surface roughness compared with that of high-speed dry EDM. Laio et al. [16] used electrolyte that added Sodium Dodecyl Sulfate (SDS) in the electrochemical discharge machining method to machine quartz workpieces. Comparison experiments were done. Results showed that the current density was increased, and there was more bubble release around the electrode as compared with that when machining in the electrolyte without SDS. The sparks become brighter and took place in a larger area, and a more stable pulse current was obtained. Therefore, higher machining efficiency, better machining quality and machining precision could be obtained in the new working fluid. Furthermore, researchers improved the surface
mechanical properties, increased the machining efficiency, and improved the machining quality through adding powder particles to the working medium in EDM process [17-19].

Replace the conventional electrical discharge dielectric medium by the abrasive jet flow, a new machining method called the composite machining method of abrasive jet and electrical discharge, is proposed. The experimental setup and machining principle of the composite machining method is illustrated. The breakdown property is analyzed using the Laplace's equation and its solution equation of the Gauss's law in the differential form in the spherical coordinates.

2. The composite machining method of abrasive jet and electrical discharge
The schematic diagram of the experimental setup used in the composite machining method of abrasive jet and electrical discharge is shown in figure 1.

![Figure 1. The schematic diagram of the experimental setup.](image)

The fluid with high pressure flows into the mixing unit throwing the entrance of the fluid with high pressure. The abrasive is in the abrasive box. The abrasives in the abrasive box are transported into the mixing unit through the delivery line. In the mixing unit, the abrasives are mixed in the fluid with high pressure, and then transported into the entrance of the working medium on side of the main shaft of the EDM machine tool through the exit of the mixing unit. Whereafter, the high-pressure fluid with abrasives is sent into the discharge gap between the tool and the workpiece through the central hole of the tool electrode.

The composite machining method of abrasive jet and electrical discharge uses the high-pressure fluid with abrasives instead of the conventional EDM fluid. The debris could be ejected from the discharge gap timely so the discharge condition is improved. Meanwhile, the material could be removed easily with a lower speed of the abrasive jet when compared with the conventional abrasive jet machining method due to the reason that the material has been soften by the electro discharge. When the abrasives are used, the discharge is easier to be induced. As a result, the formation time of the discharge channel is reduced tremendously. Therefore, the machining quality and machining efficiency could be improved.

The processing principle of the composite machining method of abrasive jet and electrical discharge is shown in figure 2. The high-pressure fluid with abrasives is ejected from the nozzle. The three-phase flow is generated after impacting the air around. Subsequently, the three-phase flow acts on the electrode and the workpiece. The high-pressure fluid is the continuous phase in the liquid state. The abrasive is the dispersed phase in the solid state. The air mixed in is the dispersed phase in the gaseous state. The usage of the air-liquid-solid three phase flow could improve the dielectric property of the EDM dielectric medium. The breakdown process is influenced prominently afterwards.
Figure 2. The schematic diagram of the processing principle.

3. The theoretical basis for the influences of impurities on the continuous dielectric medium

During the EDM processing, the discharge gap between the tool electrode and the workpiece is very small and uniform. Therefore, if the dielectric medium is pure enough, it is usually thought that the electric field is homogeneous field. However, for the composite machining method of abrasive jet and electrical discharge, the dispersed phases in the gaseous state and the solid state are mixed into the pure liquid dielectric medium. The dispersed phases in the gaseous state and the solid state are impurities for the pure continuous liquid dielectric medium. The dielectric coefficients of impurities are different from the pure continuous liquid dielectric medium. This could cause the distortion of the electric field between the tool electrode and the workpiece during the EDM processing. The dielectric properties of the working medium are changed, as a result, its breakdown course is changed.

The breakdown property for the dielectric medium of the composite machining method of abrasive jet and electrical discharge is analyzed using the Laplace’s equation and its solution equation of the Gauss’s law in the differential form in the spherical coordinates. The Laplace’s equation of the Gauss’s law in the differential form in the spherical coordinates is equation (1). Its solution equation is equation (2), equation (3) and equation (4). Among which $p_n(cos\theta)$ is the nth first class legendre function; $q_n(cos\theta)$ is the nth second class legendre function; $P_n(cos\theta)$ is the nth first class legendre polynomial expansion; $Q_n(cos\theta)$ is the nth second class legendre polynomial expansion; $P_{nm}(cos\theta)$ is the first class combined-form legendre function; $Q_{nm}(cos\theta)$ is the second class combined-form legendre function.

\[ \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) + \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial V}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 V}{\partial \phi^2} = 0 \]  

(1) when $m=0$ and $n$ is an arbitrary constant

\[ V = \left( B_1 r^n + B_2 \frac{1}{r^{n+1}} \right) \left[ C_1 P_n(cos \theta) + C_2 Q_n(cos \theta) \right] \]

(2) when $m=0$ and $n$ is an integer

\[ V = \left( B_1 r^n + B_2 \frac{1}{r^{n+1}} \right) \left[ C_1 P_n(cos \theta) + C_2 Q_n(cos \theta) \right] \]

(3) when $m \neq 0$, $m$ is an integer, and $n$ is an integer

\[ V = \left( B_1 r^n + B_2 \frac{1}{r^{n+1}} \right) \left[ A_1 \cos(m\phi) + A_2 \sin(m\phi) \right] \left[ C_1 P_{nm}(cos \theta) + C_2 Q_{nm}(cos \theta) \right] \]

(4)

When there are impurities in the pure continuous dielectric medium, the maximum of the electric field strength that could be caused by the impurities can be calculated by equation (5) and equation (6) [20]. Among which $E_0$ is the critical electric field strength of the pure continuous dielectric medium; $\varepsilon_1$ the dielectric coefficient of the pure continuous dielectric medium; $\varepsilon_2$ is the dielectric coefficient of the impurity. When the dielectric coefficient of the impurity is larger than the pure continuous dielectric medium, equation (5) could be applied. When the dielectric coefficient of the impurity is smaller than the pure continuous dielectric medium, equation (6) could be used.

\[ E_M = \left[ 1 + 2(\varepsilon_2 - \varepsilon_1)(\varepsilon_2 + 2\varepsilon_1)^{-1} \right] E_0 \]  

(5)
\[ E_M = [1 + (\varepsilon_1 - \varepsilon_2)(\varepsilon_2 + 2\varepsilon_1)^{-1}]E_0 \]  

4. Analysis of the breakdown characteristics of the composite machining method of abrasive jet and electrical discharge

4.1. Influence of each kind of impurities on the dielectric strength of the continuous phase

For the composite machining method of abrasivejet and electrical discharge, the pure working medium is the dielectric medium in the liquid state, the impurities are the abrasive phase and the air bubble phase. When different kinds of abrasive phase and dielectric medium in the liquid state are used, the dielectric properties of the dielectric medium for the composite machining method of abrasive jet and electrical discharge are different. Six cases are considered in the following analysis and calculation.

4.1.1. Dielectric strength for the EDM fluid and the conductive abrasive. When the EDM fluid is selected as the dielectric medium in the liquid state, the dielectric coefficient of the liquid phase is \( \varepsilon_1=2.07\varepsilon_0 \). Among which, \( \varepsilon_0 \) is the dielectric coefficient of the vacuum. When the conductive particles are selected as the abrasive phases, it is generally recognized that its dielectric coefficient is infinite, namely, the dielectric coefficient of the impurities in the solid state is \( \varepsilon_2=\infty \). Due to the reason that the dielectric coefficient of the impurities in the solid state is larger than the continuous EDM fluid in the liquid state, equation (5) is used to calculate the maximum dielectric strength \( E_M \) that is caused by the impurities in the solid state. The result is \( E_M=3E_0 \).

According to the calculated result, the dielectric strength needed to breakdown the dielectric medium between the tool electrode and the workpiece is changed to \( E_0=E_M/3\approx0.33E_M \), due to the addition of the impurities in the solid state.

4.1.2. Dielectric strength for the EDM fluid and the air bubble. Using the EDM fluid as the dielectric medium in the liquid state, the dielectric coefficient of the liquid phase is \( \varepsilon_1=2.07\varepsilon_0 \). It is generally recognized that the dielectric coefficient of the air is approximately equal to the dielectric coefficient of the vacuum, namely, the dielectric coefficient of the air bubble impurities is \( \varepsilon_2\approx\varepsilon_0 \). The dielectric coefficient of the air bubble impurities is less than that of the EDM fluid. Therefore, the maximum electric field strength \( E_M \) caused by the addition of the air bubble impurities should be calculated by equation (6). The result is \( E_M=1.208E_0 \).

Thus, the addition of the air bubble impurities results in the variation of the electric field strength for the breakdown of the dielectric medium between the tool electrode and the workpiece. The changed value for the breakdown is \( E_0=E_M/1.208\approx0.83E_M \).

4.1.3. Dielectric strength for the EDM fluid and the \( \text{Al}_2\text{O}_3 \) non-conductive abrasive. Using the EDM fluid as the dielectric medium in the liquid state, the dielectric coefficient of the liquid phase is \( \varepsilon_1=2.07\varepsilon_0 \). Selected the \( \text{Al}_2\text{O}_3 \) non-conductive abrasive as the impurity phase, the dielectric coefficient for the impurities phase is \( \varepsilon_2=6.5\varepsilon_0 \). Due to the reason that the dielectric coefficient of the impurities in the solid state is larger than that in the liquid state, equation (5) is used to calculate the maximum electric field strength \( E_M \) caused by the addition of the impurities in the solid state. The result is \( E_M=1.833E_0 \).

Obviously, the addition of the \( \text{Al}_2\text{O}_3 \) non-conductive abrasive leads to the change of the breakdown electric strength for the breakdown of the dielectric medium between the tool electrode and the workpiece. The value for the breakdown is changed to \( E_0=E_M/1.833\approx0.55E_M \).

4.1.4. Dielectric strength for the water and the conductive abrasive. When the water is selected as the dielectric medium in the liquid state, the dielectric coefficient of the liquid phase is \( \varepsilon_1=80\varepsilon_0 \). Selected the conductive particles as the abrasive phases, the dielectric coefficient of the impurities in the solid state is \( \varepsilon_2=\infty \). Due to the reason that the dielectric coefficient of the impurities in the solid state is
larger than the continuous dielectric in the liquid state, equation (5) is used to calculate the maximum dielectric strength \( E_M \) that is caused by the impurities in the solid state. The result is \( E_M = 3E_0 \).

Therefore, the dielectric strength that is needed to breakdown the dielectric medium between the tool electrode and the workpiece is changed to \( E_0 = E_M / 3 \approx 0.33E_M \), due to the addition of the impurities in the solid state.

### 4.1.5. Dielectric strength for the water and the air bubble.

Using water as the dielectric medium in the liquid state, the dielectric coefficient of the liquid phase is \( \varepsilon_1 = 80\varepsilon_0 \). Moreover, the dielectric coefficient of the air bubble impurities is \( \varepsilon_2 = \varepsilon_0 \). The dielectric coefficient of the air bubble impurities is less than that of the water. Therefore, the maximum electric field strength \( E_M \) caused by the addition of the air bubble impurities should be calculated by equation (6). The result is \( E_M = 1.491E_0 \).

As a result, the addition of the air bubble impurities results in the variation of the electric field strength for the breakdown of the dielectric medium between the tool electrode and the workpiece. The changed value for the breakdown is \( E_0 = E_M / 1.491 \approx 0.67E_M \).

### 4.1.6. Dielectric strength for the water and the Al\(_2\)O\(_3\) non-conductive abrasive.

Using water as the dielectric medium in the liquid state, its dielectric coefficient is \( \varepsilon_1 = 80\varepsilon_0 \). Selected the Al\(_2\)O\(_3\) non-conductive abrasive as the impurity phase, the dielectric coefficient for the impurities phase is \( \varepsilon_2 = 6.5\varepsilon_0 \). The dielectric coefficient of impurity phase is less than that of the water. Therefore, the maximum electric field strength \( E_M \) caused by the addition of the Al\(_2\)O\(_3\) non-conductive abrasive impurities should be calculated by equation (6). The result is \( E_M = 1.441E_0 \).

So, the addition of the Al\(_2\)O\(_3\) non-conductive abrasive leads to the change of the breakdown electric strength for the breakdown of the dielectric medium between the tool electrode and the workpiece. The value is changed to \( E_0 = E_M / 1.441 \approx 0.69E_M \).

### 4.2. Analysis of the breakdown property of the multiphase medium

The working medium in the liquid state that usually used in the EDM process contains the EDM fluid and water. The working medium in the solid state that could be used in the composite machining method of abrasive jet and electrical discharge includes conductive abrasives and non-conductive abrasives. Select the Al\(_2\)O\(_3\) abrasives that usually used in the traditional grinding as the non-conductive abrasives. For the composite machining method of abrasive jet and electrical discharge, the abrasive jet flow ejects from the nozzle, impacts the air around the nozzle, and then generates the gas-liquid-solid three phase flow. The three-phase flow is used as the new EDM working fluid and enters into the discharge gap between the tool electrode and the workpiece electrode. According to the calculations in section 4.1, assume the concentration and the distribution of each kind of impurity phase are the same, analyze the influence of each kind of impurity phase on the dielectric strength of the working medium in the liquid phase.

Compared with the dielectric strength of the pure EDM fluid, the addition of the conductive abrasives could reduce the dielectric strength of the dielectric medium in the discharge gap at most about 0.67 times; the addition of the air impurity could reduce the dielectric strength at most about 0.17 times; the addition of the Al\(_2\)O\(_3\) non-conductive abrasives could reduce the dielectric strength at most about 0.45 times. When the EDM fluid is used as the liquid continuous phase, the addition of the impurity in the solid state could further reduce the dielectric strength of the dielectric medium compared with the air impurity. For the conductive abrasive and the Al\(_2\)O\(_3\) non-conductive abrasive, the addition of the conductive abrasive is more beneficial to reduce the dielectric strength of the dielectric medium in the discharge gap.

Compared with the dielectric strength of the water pure dielectric medium, the addition of the conductive abrasive impurity could reduce the dielectric strength of the dielectric medium about 0.67 times at most; the addition of the air impurity could reduce the dielectric strength about 0.33 times at most; the addition of the Al\(_2\)O\(_3\) non-conductive abrasive could reduce the dielectric strength about 0.31 times at most. When the water is used as the continuous phase in the liquid state, the influence of the
air impurity and the Al$_2$O$_3$ non-conductive abrasive on the dielectric strength of the continuous phase are similar; while the addition of the conductive abrasive is more facilitate to reduce the dielectric strength of the continuous phase in the liquid state.

5. Conclusions
The composite machining method of abrasive jet and electric discharge is proposed. The experimental setup is illustrated. The machining principle is introduced. And then the machining characteristic and the superiority of this new process is analyzed.

Based on the Laplace's equation and its solution equation of the Gauss's law in the differential form in the spherical coordinates, analysis is done on the breakdown characteristics of the composite machining method of abrasive jet and electric discharge. Using the EDM fluid and the water as the continuous phases in the liquid state respectively, using the air as the impurity phase in the gaseous state, using the conductive abrasive and the Al$_2$O$_3$ non-conductive abrasive as the impurity phase in the solid state respectively, calculations are done on the maximum dielectric strength of the EDM fluid continuous phase and the conductive abrasive impurity phase, the EDM fluid continuous phase and the Al$_2$O$_3$ non-conductive abrasive impurity phase. They are about 0.33 times, 0.83 times and 0.55 times of the dielectric strength of the pure EDM fluid. Calculations are done on the maximum dielectric strength of the water continuous phase and conductive abrasive impurity phase, the water continuous phase and the air impurity phase, the water continuous phase and the Al$_2$O$_3$ non-conductive abrasive impurity phase. They are about 0.33 times, 0.67 times and 0.69 times of the dielectric strength of the pure water continuous phase.

Upon the above calculating results, analysis is done on the breakdown characteristics of the composite machining method of abrasive jet and electric discharge. The analysis indicates that the dielectric strength of the continuous phase in the liquid state could be reduced obviously by the conductive abrasive impurity phase when the concentration and the distribution are assumed to be the same. When the EDM fluid is used as the dielectric medium in the liquid state, the ability to reduce the dielectric strength of the continuous phase in the liquid state of the Al$_2$O$_3$ non-conductive abrasive impurity phase is about 2.6 times of that of the air impurity phase. When the water is used as dielectric medium in the liquid state, the ability to reduce the dielectric strength of the continuous phase in the liquid state of the Al$_2$O$_3$ non-conductive abrasive impurity phase is similar to that of the air impurity phase.

When the water-air-Al$_2$O$_3$ non-conductive abrasive is used as the dielectric medium of the composite machining method of abrasive jet and electrical discharge, the relative content ratio of the air impurity phase and the Al$_2$O$_3$ non-conductive abrasive phase in the continuous phase in the liquid state influences the dielectric strength of the continuous phase in the liquid state slightly. The dielectric property of the three-phase jet flow is more stable. Therefore, the EDM processing is more stable.

When the conductive abrasive-air-EDM fluid is used as the dielectric medium of the composite machining method of abrasive jet and electrical discharge, the relative content ratio of the air impurity phase and the conductive abrasive phase in the continuous phase in the liquid state influences the dielectric strength of the continuous phase in the liquid state greatly. Hence, different dielectric property of the three-phase jet flow could be obtained by adjusting the relative content ratio of the air impurity phase and the conductive abrasive phase in the continuous phase in the liquid state. This makes the processing of the composite machining method controllable.

Acknowledgements
The authors acknowledge support by a grant from the Natural Science Foundation of Shandong Province (grant no. ZR2016EEB14) in China, and a grant from the Natural Science Foundation of Shandong Province (grant no. ZR2018MEE028) in China.
References
[1] Yin QF, Wang XQ, Wang P, Qian ZQ, Zhou L and Zhang YB 2016 Fabrication of micro rod electrode by electrical discharge grinding using two block electrodes Journal of Materials Processing Technology 234 143–9
[2] Kozak J, Zybura-Skrabalak M and Skrabalaka G 2016 Development of advanced abrasive electrical discharge grinding (AEDG) system for machining difficult-to-cut materials Procedia CIRP 42 872–7
[3] Satyarthi MK and Pandey PM 2013 Modeling of material removal rate in electric discharge grinding process International Journal of Machine Tools & Manufacture 74 65–73
[4] Kremer D, Lebrun JL, Hosari B and Moisan A 1989 Effects of ultrasonic vibrations on the performances in EDM CIRP Annals 38 199–202
[5] Abbas NM, Solomon DG and Bahari MF 2007 A review on current research trends in electrical discharge machining(EDM) International Journal of Machine Tools & Manufacture 47 1214–28
[6] Lin YC, Hung JC, Chow HM, Wang AC and Chen JT 2016 Machining characteristics of a hybrid process of EDM in gas combined with ultrasonic vibration and AJM Procedia CIRP 42 167–72
[7] Goiotgana M, Sarasua JA, Ramos JM, Echavarri L and Cascón I 2016 Pulsed ultrasonic assisted electrical discharge machining for finishing operations International Journal of Machine Tools & Manufacture 109 87–93
[8] Kurniawan R, Kumaran ST, Prabu VA, Zhen Y, Park KM, Kwak YI, Islam MM and Ko TJ 2017 Measurement of burr removal rate and analysis of machining parameters in ultrasonic assisted dry EDM (US-EDM) for deburring drilled holes in CFRP composite Measurement 110 98–115
[9] Paula L and Korah LV 2016 Effect of power source in ECDM process with FEM modeling Procedia Technology 25 1175–81
[10] Singh T and Dvivedi A 2016 Developments in electrochemical discharge machining: A review on electrochemical discharge machining, process variants and their hybrid methods International Journal of Machine Tools & Manufacture 105 1–13
[11] Kang XM and Tang WD 2018 Micro-drilling in ceramic-coated Ni-superalloy by electrochemical discharge machining Journal of Materials Processing Technology 255 656–64
[12] Zhang Y, Xu ZY, Xing J and Zhu D 2016 Effect of tube-electrode inner diameter on electrochemical discharge machining of nickel-based superalloy Chinese Journal of Aeronautics 29 1103–10
[13] Elhami S and Razfar MR 2016 Analytical and experimental study on the integration of ultrasonically vibrated tool into the micro electro-chemical discharge drilling Precision Engineering 47 424–33
[14] Chakraborty S, Dey V and Ghosh SK 2015 A review on the use of dielectric fluids and their effects in electrical discharge machining characteristics Precision Engineering 40 1–6
[15] Shen Y, Liu YH, Sun WY, Zhang YZ, Dong H, Zheng C and Ji RJ 2016 High-speed near dry electrical discharge machining Journal of Materials Processing Technology 233 9–18
[16] Laio YS, Wu LC and Peng WY 2013 A study to improve drilling quality of electrochemical discharge machining (EDCM) process Procedia CIRP 6 609–14
[17] Toshimitsu R, Okada A, Kitada R and Okamoto Y 2016 Improvement in Surface Characteristics by EDM with Chromium Powder Mixed Fluid Procedia CIRP 42 231–5
[18] Abdul-Rani AM, Nanimina AM, Ginta TL and Razak MA 2017 Mached surface quality in nano aluminum mixed electrical discharge machining Procedia Manufacturing 7 510–17
[19] Bai X, Zhang QH, Zhang JH, Kong DZ and Yang TY 2013 Machining efficiency of powder mixed near dry electrical discharge machining based on different material combinations of tool electrode and workpiece electrode Journal of Manufacturing Processes 15 474–82
[20] Li MH 1989 *Theoretical Basis of the Electrical Discharge Machining Method* (Beijing: National Defence Industry Press) pp 50–1